EXPERIMENTAL STUDY OF FLOW THROUGH RIGID VEGETATION IN OPEN CHANNEL

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of

Master of Technology
in
Civil Engineering

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DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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2015

National Institute of Technology
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CERTIFICATE

This is to certify that the thesis entitled "**Experimental Study of Flow through Rigid Vegetation in Open Channel**" being submitted by Kajal Panigrahi in partial fulfilment of the requirements for the award of **Master of Technology** in **Civil Engineering** at National Institute of Technology Rourkela, is a bonafide research carried out by her under our guidance and supervision.

The work incorporated in this thesis has not been, to the best of our knowledge, submitted to any other University or Institute for the award of any degree or diploma.

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Kajal Panigrahi

ABSTRACT

The present study investigates the various hydraulic characteristics of vegetated open channel under both emergent and submerged flow conditions with various discharges and flow depths. Cylindrical rigid iron rods of height 10 cm and diameter 6.5 mm planted in staggered pattern in a tilting hydraulic flume with a vegetal density of 76 per unit bed area of 1 m^2 are used to simulate the effect of hydraulic characteristics on vegetation in open channel.

Measurement of flow velocity inside the stem/vegetation layer under emergent condition indicates that the velocity profile is one layer with almost a uniform constant velocity at all points along the path of longitudinal direction of flow. However, under submerged flow condition, velocity of flow in the surface layer above the top of vegetation is very high and follows logarithmic law. The various hydraulic resistances like vegetal drag coefficient, C_D, Manning's roughness coefficient n, and Darcy-Weisbach friction factor, f are found to be more for vegetated open channel than open channel without any vegetation. These resistance factors are found to vary with flow depths and submergence ratios whereas channel without vegetation bears a constant roughness coefficient. Under submerged flow conditions, when the depth of flow increases, values of n and f are found to decrease but values of C_D are found to increase. However, under emergent flow conditions, reverse trends are noticed. Values of C_D, n and f are found to increase with increasing depth of flow.

Equations have been shown to predict the stem/vegetation layer velocity under both emergent and submerged flow cases. The calculated velocities are found to be close to the observed velocities indicating that the developed equation can be used to predict the flow for both emergent and submerged conditions. Further, regression based multi-linear models are developed relating to drag coefficient and various hydraulic and vegetative parameters for both emergent and submerged flow conditions and the models are found to work satisfactorily after validation with the present experimental data and data of other investigators.

Keywords: vegetated open channel, staggered pattern, vegetal density, stem layer, surface layer, vegetal drag coefficient C_D, Manning's roughness coefficient n, Darcy-Weisbach friction factor f, submergence ratio, multi-linear model.

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LIST OF ABBREVIATIONS AND SYMBOLS

ADV Acoustic Doppler Velocimeter

MPE Mean Percentage Error

MAPE Mean Absolute Percentage Error

RMSE Root Mean Square Error

A Area of channel cross section

B Channel width

B/h Aspect ratio

B_c Minimum channel flow width in the stem layer

C Chezy's channel coefficient

C_b Chezy's coefficient for the channel bed

C_D Drag coefficient of a stem based on V_c

d Stem diameter

dh Distance between two consecutive points in the vertical direction where velocity, v is measured

e_b Relative bed roughness

f Darcy-Weisbach's friction factor

f'' Friction factor due to form roughness

f' friction factor due to sand grain roughness

f_b Bed friction factor

Fr Froude Number

F_v Velocity coefficient which depends on l^*

f_w Side wall friction factor

f_{wR} Rough side wall friction factor

f_{wS} Smooth side wall friction factor

g Acceleration due to gravity

h Flow depth

k Deflected vegetation height

k_s Equivalent sand grain diameter for bed roughness

k_{sb} Equivalent bed roughness height

k_{sw} Equivalent wall roughness height

l Wetted stem length

l^*	Submergence ratio
n	Manning's roughness coefficient
N	Number of stems per unit bed area
Q	Channel discharge
R	Hydraulic radius, defined as flow area/wetted perimeter
R^2	Coefficient of Determination
Re	Reynolds Number
$R_{e(b)}$	Reynolds Number for evaluating the bed friction factor
$R_{e(d)}$	Cylinder Reynolds Number
r_v	Vegetation related hydraulic radius
r_v^*	Dimensionless vegetation related hydraulic radius
r_{vm}	Corrected vegetation related hydraulic radius (with bed and side wall correction)
S	Channel bed slope
s	Stem spacing
S_b	Portion of friction slope attributable to bed shear
S''_f	Energy slope associated with drags on vegetated elements
S'_f	Energy slope associated with soil boundary
S_f	Total energy line slope
S_v	Portion of friction slope attributable to stem drag
U	Measured velocity by manometer
V	Mean channel velocity
v	Velocity at any point in the vertical plane of the flow
V_c	Average velocity in stem layer at constricted section (i.e. Mean constricted channel velocity)
V_k	Constant velocity within vegetation
V_l	Average velocity in stem layer
V_s	Average velocity in surface layer
α	Exponent
Δh	Difference in water elevation in manometer
Δp	Pressure difference in manometer
θ	Angle of manometer with horizontal base
λ	Area concentration of stems
ν	Kinematic viscosity of water
ξ	Parameter representing the stem (cylinder) staggering pattern

ρ	Water density
τ_b	Bed resistance exerted on water in streamwise direction per unit bed area
τ_v	Stem drag resistance exerted on water in streamwise direction per unit bed area
τ_w	Gravity force of water in streamwise direction per unit bed area

CHAPTER 1

INTRODUCTION

INTRODUCTION

1.1 General

Establishment of a satisfactory waterway for handling runoff from agricultural as well as urban areas is one of the important problems faced by hydraulic engineers in planning an economical and effective conservation system. The problem aggravates more in sloping areas where water flows with high velocity causing scouring and sediment deposition in natural channels and rivers thereby altering the conveyance capacity. Safe disposal of runoff in these areas need immediate attention so that costly agricultural lands and hydraulic structures, loss of human and other lives as well as physical and biological process in aquatic environment are least affected. Vegetated open channels can play an effective role in such contexts with least investment.

Vegetations in an open channel retards the flow of water by causing a loss of energy through turbulence and exerting additional drag forces on the moving water. Vegetations that grow in the beds and sides of open channels and flood plain areas increase the resistance to flow and hence play a vital role in sediment, nutrient, and pollutant concentration. Efforts are now being made at the global level for restoration and rehabilitation of the waterways, flood plain management and restoration of river ecosystems and for this purpose, vegetation has immense contribution.

When vegetations such as shrubs, herbs, trees, bushes etc. grow naturally on the channel beds and river banks, it is called a naturally vegetated open channel. In some cases, vegetations are planted along the beds and banks of channels and rivers which are called artificially vegetated open channel. Figs. 1.1 and 1.2 represent views of naturally and artificially vegetated open channels.

Fig. 1.1 Naturally vegetated open channel

Fig. 1.2 Artificially vegetated open channel

1.2 Need for Research

An important property of vegetated open channel is to resist the flow by boundary shear stress as well as drag force induced by the stems and foliages. The stem or vegetation drag coefficient is frequently used as the parameter representing the resistance to flow by the vegetation. The drag coefficient of a vegetated open channel depends on a number of factors including channel geometry, vegetation configurations, surface characteristics of channel boundary and vegetation characteristics including height, density and thickness of vegetations, its degree of bending to flow, and submergence ratio. Even though a number of investigators have studied the different aspects of hydraulic parameters of vegetated open channel flow including drag coefficient, due to limited understanding of complex physics inherent in relevant flow phenomena, difficulties still arise in evaluation of vegetation resistance using conventional Manning's, Chezy's and Darcy-Weisbach formulae (Yen, 2002; Zima and Ackermann, 2002). Review of works of various investigators also indicate that resistance characteristics of relatively smooth boundaries roughened by large roughness elements such as vegetations are yet to be fully understood. Studies in open channel flow under submerged and emergent condition with vegetation in beds simulating different types of roughness elements can provide a better understanding on flow resistance. However, naturally occurring vegetation varies with geometric characteristics and distribution density with time which causes complexity in flow analysis. Rigid cylinders with well defined geometric characteristics and distribution density can alternatively be used to simulate vegetation and can provide a better understanding in study of flow resistance (Wessels and Strelkoff, 1968; Li and Shen, 1973; Stone and Shen, 2002; Cheng and Nguyen, 2011).

Because of practical difficulties in obtaining sufficiently accurate and comprehensive data in actual field experiments, well designed laboratory studies are preferred as a truthful method to provide information concerning details of the hydraulic parameters. Such information is important in application and development of numerical models that can help to predict hydraulic resistance and determine the velocity distribution in vegetated open channel.

After extensive review of various literature, it is felt necessary to have a detailed and comprehensive research in the laboratory to evaluate the different hydraulic parameters including drag coefficient and retardance coefficient of vegetated open cannel with rigid cylindrical stems under submerged as well as emergent case with varying discharges and depths.

1.3 Scope of the Study

The present series of experiments on vegetative channels at N.I.T. Rourkela undergo two varieties of flow conditions (i) Submerged flow and (ii) Emergent flow; is a step to understand flow process in a vegetative channel for different hydraulic conditions. The current study presents the variation of drag coefficient, C_D and roughness coefficient, n with vegetation density, Froude Number, Reynolds Number, Aspect ratio and Submergence ratio. This analysis on drag coefficient and roughness coefficient gives an insight into the flow mechanism and resistance relationships of a vegetative channel.

1.4 Organization of the Thesis

The thesis comprises of six chapters.

Chapter 1 presents a brief introduction of the research. The need for the research, scope and objectives of the present study along with the relevant background information are included in this chapter.

Chapter 2 presents the review of literature of various pioneering investigators in the field of vegetated open channels. The work done by the various researchers on hydraulic resistances including vegetation drag coefficient, Manning's roughness coefficient, Darcy-Weisbach friction factor, velocity distributions, and other hydraulic parameters including Reynolds Number are presented in Chapter 2.

Chapter 3 describes experimental program which includes experimental channel design, design and construction of roughness elements, experimental procedure for different channel geometry, and discharge and velocity measurement.

Chapter 4 includes theoretical considerations for evaluation of various parameters like drag coefficient, Manning's roughness coefficient, Darcy-Weisbach's friction factor and prediction of velocity within stem/vegetation layer and surface layer.

Chapter 5 presents the results and discussions of various experimental data obtained in the study. Results concerning different types of hydraulic resistance, velocity distributions, relations of various types of hydraulic resistance with hydraulic parameters like aspect ratio, submergence ratio, Reynolds Number etc., are vividly discussed in this chapter. Longitudinal velocity profile with varying depths of flow for both submerged and emergent conditions has been presented. It has been observed that the estimated mean channel velocity by Stone and Shen (2002) always overestimates the experimentally measured mean channel velocity.

Chapter 6 is the last chapter of the thesis. Salient findings of the research work both for submerged and emergent flow conditions are briefly narrated in this chapter.

Scope for the future research work is also presented after the section conclusion. Various references that have been reviewed for the present thesis work are listed at the end of the dissertation.

CHAPTER 2

LITERATURE REVIEW

LITERATURE REVIEW

This chapter includes a brief review of various research work done by various researchers in evaluation of hydraulic characteristics of vegetated open channels. Hydraulic resistance and velocity distributions are the two important hydraulic characteristics of vegetated open channels. Works on both natural and simulated vegetation under both emergent and submerged condition of flow are reviewed and presented in this chapter.

2.1 Hydraulic Resistance

For determination of stage-discharge characteristics of a river or a channel section, hydraulic engineers require basic knowledge of flow resistance and conveyance for the channel section. For the analysis of river flows, a number of well-established flow resistance formulae are used. Some of the important flow resistance formulae are Darcy-Weisbach equation, Chezy's and Manning's formulae as well as stem/vegetation drag coefficient formula. A number of literature on flow over rough channel or pipe boundaries are available. However, the resistance characteristics of relatively smooth boundaries roughened with large roughness elements are not well understood. Studies on open channel flows in roughened beds can provide a better understanding in study of flow resistance.

Flow resistance in open channel flow is very complicated and there are no exact methods to determine it (Jarvela, 1998). The various factors that influence the flow resistance in an open channel are size, shape and irregularity of the channel, channel sinuosity, types of roughness and vegetation including its length, density and stiffness (Chow, 1959). Vegetation that grow in the channel bed and flood plain areas increase the flow resistance and reduce the conveyance. Stem/vegetation drag is one of the important flow resistance parameter in vegetated open channels.

2.1.1. Vegetation Drag Coefficient

Several investigators have studied the effect of flow depth, vegetation; its height, density and vegetal stiffness under both emergent and submerged conditions on flow resistance of vegetated open channels. Some of the notable contributions in this field are discussed below. Fenzl (1962) using inflexible thin wire rods conducted an extensive laboratory studies to evaluate flow resistance including vegetal drag coefficient and proposed several empirical formulae to evaluate drag coefficient. However, these empirical formulae have limitation in their applicability since they were developed with considerations of lower values of area concentrations up to 0.81% only.

Kouwen et al. (1969) conducted a laboratory study using polyethylene plastic strips to simulate vegetation. They developed some empirical formulae to compute channel average velocity which is used to estimate drag coefficient. Similar to Fenzl (1962), these formulae have limitations that they were developed without considerations of large number of values of roughness area concentrations.

Petryk (1969) studied drag forces on individual cylinders in different multi-cylinder arrangements under a variety of open channel flows. He studied the effect of decay and spread characteristics of wakes that form behind the cylinders on computation of drag coefficient. Under emergent condition of flow, an analytical flow resistance model was developed in this study to evaluate the drag coefficient. The study investigated the influence of a neighbouring cylinder on the drag measured at a test cylinder and reported that when the cylinders are sufficiently close, the mean drag on the pair of cylinders could be either smaller or greater than that of an isolated cylinder depending on the orientation of the cylinders.

Stem drag coefficient depends on a number of factors like stem height, diameter, spacing, distribution patterns and density. Li and Shen (1973) theoretically investigated the relations among stem drag coefficient and stem staggering patterns and reported that stem staggering patterns had great influence on flow resistance by affecting the stem drag coefficient.

Blevins (2005) as well as Zdravkovich and Pridden (1977) established drag coefficient study with aquatic plant stem. They found that values of drag coefficient, C_D decreased with increasing values of Reynolds Number. They further noticed that values of C_D were influenced by the presence and relative position of neighbouring cylinders.

Using rubberized horse hair matters that simulate bush type vegetation in open channel, Wu et al. (1999) reported that vegetal drag coefficient was proportional to the Reynolds Number with a power form relation. They reported that values of C_D increase with increasing depth in a vegetated channel. However, their studies did not involve the interactions of various vegetation densities which are important variables deciding the values of C_D.

Ishikawa et al. (2000) and Kothyari et al. (2009) used strain gauge to measure the drag force exerted on a typical cylindrical stem placed in the middle of a vegetation zone. Ishikawa et al. (2000) plotted the drag coefficient against the Reynolds Number and noticed significant changes in the drag coefficient although its dependence on Reynolds Number was not clearly established. However, Kothyari et al. (2009) observed that drag coefficient varied slightly with Reynolds Number and values of C_D increased with increase in vegetation density. However, their studies were limited to short vegetation zones which may not allow the vegetated flow to be fully developed particularly in low vegetation density zone.

Stone and Shen (2002) conducted a series of laboratory experiments with circular cylindrical roughness elements of various sizes and concentrations under both emergent and submerged conditions. The results showed that the drag coefficient varies with flow depth, stem concentrations, stem lengths and stem diameters. They have developed physically based flow resistance formulae to evaluate the drag coefficient, velocity though vegetation, mean channel velocity and flow velocity in the surface layers.

Effect of in-stream emergent vegetation on flow resistance and velocity distribution were studied by Nehal and Ming (2005) who used plastic blades to simulate the vegetation. They proposed a simplified model based on drag concept to evaluate the roughness coefficient under emergent condition. They observed that values of C_D increased with depth of flow under emergent condition. Moreover as the vegetation density increased, the drag coefficient was also found to increase.

Tanino and Nepf (2008) conducted experiments with relatively dense and randomly distributed circular cylinders. They observed that normalised drag force had a linear dependence on Reynolds Number. This result appears to be consistent with the Ergun equation developed for packed bed flows.

Cheng and Nguyen (2011) considered vegetation hydraulic radius by taking into account the effect of vegetation size, vegetation densities, and channel geometry in computation of drag coefficient, friction coefficient and Reynolds Number in emergent condition of flow. Their study reveals that drag coefficient decreases monotonically with Reynolds Number. They further reported that the Ergun equation if applied to vegetative waterways, would underestimate drag coefficient for low Reynolds Number and overestimate drag coefficient for high Reynolds Numbers. They also proposed bed and side wall corrections for evaluation of drag coefficient.

Other notable contributions to the study on the drag coefficient, C_D in vegetated waterways are made by Petryk and Bosmajian (1975), Tsujimoto (1999), Kouwen and Fathi-Moghadam (2000), Carollo et al. (2002), Hashimoto and Park (2003) as well as Bapist (2005).

2.1.2. Manning's Roughness Coefficient

Cowan (1956) carried out a series of studies on roughness coefficient in channels lined with vegetation and reported that roughness of vegetated channels depends on five important parameters including vegetation. He suggested that all these amending values be added to a basic value of *n* for prismatic channels in order to get the total value of roughness coefficient of the channel.

Under the conditions of low discharge, with depth of flow much less than the height of vegetation and with little or no deflection of plant stems, Fenzl and Davis (1964) found the roughness or retardance coefficient *n* to increase with increasing depth of flow. But under submerged condition when the vegetation were deflected from the upright position, values of *n* varied with the product of average velocity (*V*) and hydraulic radius of the channel (*R*). *n* decreased as *VR* increased till a point was reached wherein there was no further change in roughness configuration and with further increase of *VR* values, *n* remained constant.

Different patterns of grouping of vegetation have also great impact on roughness coefficient. Li and Shen (1973) conducted an intense study on the flow of water in vegetated open channels with various patterns of grouping of vegetation and found that tall vegetation grouped into staggered patterns are much more effective in increasing retardance coefficient and hence on reducing flow rate than any other pattern for the same vegetation density. They further observed that tall vegetation planted in rows perpendicular to flow direction had a strong influence on increasing the resistance to flow.

Petryk and Bosmajian (1975) used a simple flow resistance model for emergent vegetation conditions to predict Manning's *n*. They observed that for a vegetated channel having uniform density of vegetation, Manning's *n* value was directly proportional to the two-third power of the hydraulic radius, *R*. They opined that for the flow through vegetation, drag force was the main influencing factor that offered resistance to flow than the total shear force on the channel boundary.

Using small diameter cylinders to simulate vegetation roughness elements, Thompson and Roberson (1976) developed an analytical model for determination of resistance coefficients which may be used to solve the various equations like the Chezy's, Darcy-Weisbach or Manning's equation for open channel flow.

Using flexible plastic strips in molten paraffin to simulate the natural vegetation, Kao and Barfield (1978) concluded that drag force by vegetation blades is a dominant feature for deciding Manning's n value in shallow emergent flow in a densely vegetated channel. They observed that when velocity and depth of flow increased, drag resistance and hence roughness coefficient also increased until vegetation were completely submerged. After that roughness value decreased as velocity and depth of flow increased.

Kouwen and Li (1980) considered physical flow processes and bio-mechanical properties of vegetation and provided a general method to evaluate Manning's n. They reported that Manning's n was a function of relative roughness and vegetation stiffness. They suggested a method to evaluate the flexural stiffness of natural vegetation.

Temple (1982) reported an improved method for determination of flow resistance of a vegetated channel. This method related the flow retardance potential of a vegetated channel directly to physical parameters normally familiar and available to design and practising engineers. This method is very much useful in tractive force design of vegetated waterways.

Wu et al. (1999) made an experimental laboratory study with artificial roughness to observe the variation in resistance values with depth of flow under both submerged and emergent conditions. Their findings reveal that for a given vegetation with particular density, resistance values are higher under emergent conditions than under the submerged conditions.

Righetii and Armanini (2002) reported that the values of roughness coefficient in sparsely distributed vegetation in open channel depend on degree of submergence. In the wet season with high discharge, vegetation undergoes high degree of bending resulting in complete submergence. At that time, the values of the coefficient is less as compared to the values when the vegetation are partly submerged in dry season having low flows.

A laboratory study was conducted by Sadeghi et al. (2010) with two types of vegetation density covering 100 and 50 percent of width of the channel and with three levels of flow discharge under emergent rigid vegetation conditions in floodplains. The results reveal that the resistance to flow get increased with reduced velocity of flow when the vegetation density is increased and for a given vegetation density, the resistance is directly proportional to the depth of flow.

2.1.3 Friction Factor

Friction factor is another important resistance parameter that affects the flow in an open channel. The values of friction factor depend on several parameters and primarily on those parameters that affect Manning's retardance coefficient. Amongst a host of factors, the vegetation: its type, height and density and degree of submergence are the primary dominant factors that influence the magnitude of friction factor.

For unlined channel without any vegetation and for high Reynolds Numbers the ASCE Task Force (1963) recommended that friction factor is independent of Reynolds Number and depends only on hydraulic radius for a given channel. The friction factor may increase over the fixed bed cases by the bed patterns that develop and it may decrease due to the sediment carried in suspension.

As reported by Lovera and Kennedy (1969), friction factor in open channels consists of two terms: (i) friction factor due to sand grain roughness and (ii) friction factor due to bed forms, channel irregularities and sediment load. The total friction factor is the sum of these two friction factors. Lovera and Kennedy's concepts support the earlier similar concepts proposed by Einstein and Barbarosa (1952) and Taylor and Brooks (1962).

Phelps (1970) conducted laboratory studies with shallow flow over a simulated turf surface consisting of rafia and observed that at low values of Reynolds Number, relative roughness had an influence over coefficient of friction. It was further noticed that at constant depth laminar flow, the product of friction factor and Reynolds Number was not constant but decreased with increasing values of Reynolds Number.

Kouwen and Unny (1973) observed that friction factor was a function of relative roughness and vegetation density. In erect and wavy conditions of stems in open channel flows, friction factor increases with Reynolds Number. Friction factor was also found to increase with vegetation density and relative roughness. However, at high discharge, vegetation undergoes complete waving and at that time friction factor depends on Reynolds Number: friction factor is reduced as the Reynolds Number is increased.

Bayazit (1976) observed that for flow depths larger than the roughness height, the usual logarithmic laws for velocity distribution is valid. But as the flow depth decreases such that roughness of vegetation was more than the depth of flow, velocity profile did not follow logarithmic law and friction factor tends to increase with increase in Reynolds Number.

In a laboratory study on sheet flows over the natural turf surfaces, Chen (1976) found that friction factor for laminar flow over the turf surfaces was higher than that of the paved surfaces. Friction factor was found to increase with bed slope but it decreased with Reynolds Number. But at very high Reynolds Numbers, friction factor was found to be constant.

A resistance law for vegetated bed channels was proposed by Murota et al. (1984) by which they reported that within a range of Reynolds Numbers from 10000 to 25000, friction factor decreased as the Reynolds Number increased.

2.2 Velocity Distribution

A study of velocity distribution helps to identify the magnitude of velocity at each point across a flow cross section. In this section study of velocity profile or velocity distribution by the different researchers are reviewed and presented.

Kouwen et al. (1969) presented velocity profiles observed in a laboratory flume planted with strips of styrene which simulated the vegetation and found out that the velocity profile above the vegetation layer followed logarithmic law. However, inside the vegetation layer the velocity was constant.

Temple (1986) suggested a two layered velocity profile for vegetated open channels. For depth of flow less than the bending height of vegetation, velocity distribution is almost constant and depends only on vegetation density and channel bed slope. But when the depth of flow increases such that the submerged condition occurs, velocity profile is dependent on momentum transfer in the form of turbulent shear.

Sumer et al. (1996) measured velocity profile inside and outside the sheet flow layer of movable bed in a tilting flume with four different types of sediments of varying sizes. Measured velocity profiles were found to follow logarithmic law near the bed, outside the sheet flow layer. However, inside the sheet flow layer, they satisfied power law.

Ikeda and Kanawaza (1996) measured the longitudinal velocity components over flexible bottom vegetation in an open channel flow by using laser Doppler velocity meter. They observed that velocity profile had an inflection point near the top of vegetation layer. They also observed that longitudinal component of turbulent intensity and shear stress had the maximum value at top of vegetation layer and decreased towards the free surface.

Anwar (1996) conducted a series of experiments in shallow coastal water to estimate the effects of flow uncertainties on the mean velocity distribution. The mean velocity profiles were measured during the accelerating and decelerating phases of the tidal coastal flows. The measured velocity profiles had three distinct regions, i.e., (i) inner region(adjacent to bed) (ii) outer region and (iii) overlap region. Velocity profiles in outer and overlap regions obey the log law and defect law, respectively.

A channel having gravels, dunes or vegetation creates large scale roughness in it. Flow over such a rough bed may differ considerably from those over smooth boundaries. A no slip condition occurs if the channel bed is smooth and impermeable. On the other hand, presence of vegetation obstructs the lower portion of channel flow functioning as a porous medium to reduce the flow velocity. This produces a two layered velocity profile: one above vegetation called surface layer and the second within the vegetation called stem or vegetation layer. The two layers interact in a manner that is very similar to the plane mixing layer rather than the boundary layer. The flow through the stem layer is almost uniform whereas in the surface layer it is logarithmic (Cheng and Chiew, 1998; Cheng et al., 2008).

Velasco et al. (2003) studied the effect of turbulence on flow in an open channel using plastic plants seeded in a gravel bed. Their findings revealed that minimal value of friction factor is obtained for totally deflected plants under favourable conditions where relative deflection of plant height was within 0.4 to 0.5 and this value was similar to friction factor in a non-vegetated open channel.

Cheng et al. (2012) used the plane mixing layer technology and proposed a length scale to normalise the velocity profile for vegetated open channel flows. The vegetation was simulated by arrays of rigid and cylindrical rods arranged in a staggered pattern. They used three types of rods each of height 10 cm but varying diameters ranging from 3.2 to 8.3 mm. The vegetation density varied from 0.43 to 11.9%. The new scaling is an improvement over those based on logarithmic law, velocity defect law and power law in collapsing the velocity profile.

2.3 Critical Review

Review of the various research works by the past researcher's reveal that there is a need to evaluate the hydraulic parameters like the different hydraulic resistances and velocity profiles of vegetated open channels under various flow conditions including both emergent and submerged conditions. An understanding of the flow resistance and conveyance values of channels sections will help the hydraulic engineers in design of different hydraulic structures.

The different hydraulic resistance values will be helpful in analytical model development for evaluation of hydraulic parameters in vegetated open channel flows.

2.4 Objectives of the Present Research Work

Based on the literature reviewed, accordingly the objectives of the present research work are finalized as follows:

- To investigate the variation of Manning's roughness coefficient *n*, Chezy's coefficient *C*, Darcy-Weisbach friction factor *f* with respect to the varying aspect ratio under both submerged and emergent flow conditions with vegetation.
- To analyze and study the longitudinal velocity profile along the whole depth including the stem layer and the surface layer of vegetation under different discharges and depths.
- To study the hydraulic parameters in open channel such as Reynolds Number, Froude Number, aspect ratio, submergence ratio and vegetation density. This will be useful to solve many practical problems in open channel flow with vegetation.

CHAPTER 3

EXPERIMENTAL PROGRAM

• EXPERIMENTAL PROGRAM

3.1. General

Experiments were conducted under controlled laboratory conditions in the Fluid Mechanics Laboratory of the Civil Engineering Department at the National Institute of Technology, Rourkela, India in order to find out the impact of roughness characteristics of vegetation on various hydraulic characteristics of open channel flow. The various hydraulic characteristics of flow studied were hydraulic resistances including vegetation drag coefficient C_D, Manning's roughness coefficient, n and velocity distribution of flow under both emergent and submerged conditions. Experiments were also conducted to find out Reynolds Number, Froude Number, Chezy's coefficient, C and Darcy-Weisbach's friction factor, f at different discharges and flow depths and correlate the various hydraulic parameters to develop models to predict drag coefficient and roughness coefficient in vegetated open channel flow under emergent and submerged flow conditions. This chapter describes the experimental channel design, construction of roughness elements and measurement techniques of experimental data including velocity of flow and the development of stage-discharge relationship in the hydraulic flume. Details of the various instruments used to measure the experimental data are also discussed in this chapter.

3.2. Experimental Channel Design

3.2.1. Tilting Flume

For the present study a straight simple channel in the form of a tilting flume having length 12 m, width 0.6 m and depth of 0.45 m is used. The tilting flume is made of metal frame with glass walls at the test reach. At the beginning of the flume just after inlet and before head gate (called stilling chamber), a series of baffle walls are installed for energy dissipation purpose, i.e., to reduce turbulence and to make water still before passing over the channel. Head gate reduces the waves if formed in the water body before it passes over the channel and in this way head-gate plays a vital role in maintaining uniform flow. Tailgate was provided just before end point of the flume for bed slope measurement purpose. There was provision of over bridge platform in the flume which helps in experimental works. The flume was supported on a hinge at the centre and made tilting by providing hydraulic jack arrangement at starting point of the flume. The plan view of the experimental channel used in the present study is shown in Fig. 3.1. The overall view of the flume with experimental set up is shown in Fig. 3.2.

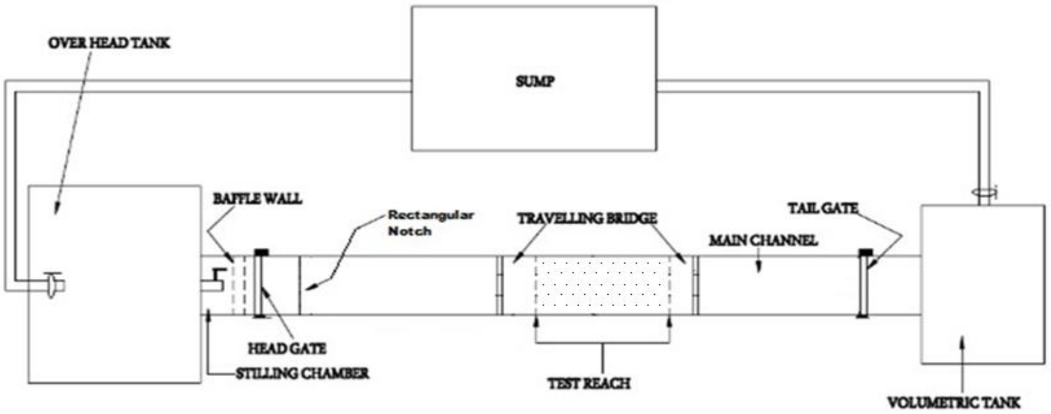

Fig. 3.1 Plan view of the experimental channel

Fig. 3.2 Overall view of the flume with experimental setup

3.2.2. Experimental Channel

Experiments are conducted in a straight simple rectangular channel with uniform cross section built inside a metallic flume. The dimensions of the channel section are: length=12 m, width=0.6 m and depth=0.45 m. Experiments are conducted at aspect ratios (aspect ratio = width of flume : depth of flow in the flume) of > 5.0 for emergent flow conditions and < 5.0 for submerged flow conditions. The whole channel is fabricated by using 19 mm thick water resistant plywood in the bed. The equivalent sand grain roughness of the plywood is found to be 0.37 mm. The slope of the flume is fixed at 0.00064 (0.064%) for all runs. The geometrical parameters of the experimental channel are mentioned in Table 3.1

Table 3.1 Geometrical parameters of the experimental channel section

Sl no.	Item description	Experimental channel
1	Channel type	Straight
2	Geometry of channel section	Rectangular
3	Channel base width (B)	0.6 m
4	Top width of channel (B)	0.6 m
5	Depth of channel (H)	0.45 m
6	Bed slope of the channel (S)	0.064%
7	Length of whole channel	12 m
8	Test Reach Length	6.5 m
9	Nature of surface of bed	Rough, rigid cylindrical vegetation

3.2.3. Water Supply System

Water for the experiment is supplied from an overhead tank to which a water level indicator is attached to show the maintaining of constant water level in the overhead tank. Two parallel pumps are installed for pumping water from an underground sump to the overhead tank. Water delivers to the stilling chamber from the overhead tank, passing over the experimental channel under gravity and is made to fall onto the volumetric tank situated at the end of the flume. From the volumetric tank, water is allowed to flow into an underground sump. Water is recirculated back from the sump.

3.3 Design and Construction of Roughness Elements

In the present study, cylindrical iron rods of diameter 6.5 mm are used to simulate vegetation stems. The rods are pre-drilled into plywood and thus are attached to the flume bed. The top of the rods averaged 0.1 m above the surface of the plywood bed. This is the stem length, l, for all experimental runs. There are two types of patterns of planting of vegetation in the bed of open channel. They are (i) parallel pattern and (ii) staggered pattern. The two types of planting patterns are shown in Fig. 3.3. In the present study, staggered pattern of rods with spacing of 10 cm are adopted. The spacing between the rods in each row and column is fixed at 10 cm (Fig. 3.4). A test reach of length 6.5 m in the centre of the tilting hydraulic flume is planted with iron rods which simulates the vegetation zone. Total number of rods planted in the 6.5 m test reach of the channel of width 0.6 m were 297 which counts to 76 per 1 m^2 of channel bed area. Detailed geometrical features of the roughness elements used in the present experiment are mentioned in Table 3.2.

Table 3.2. Detailed geometrical features of the roughness elements

Sl no.	Roughness elements	Description
1	Type	Rigid
2	Shape	Cylindrical
3	Diameter (d)	0.0065 m
4	Height	0.1 m
5	Material	Iron
6	Distribution pattern	Staggered
7	Spacing	0.1 m (bothways)
8	No. of stems per unit bed area	76
9	Test reach dimension	6.5 m x 0.6 m

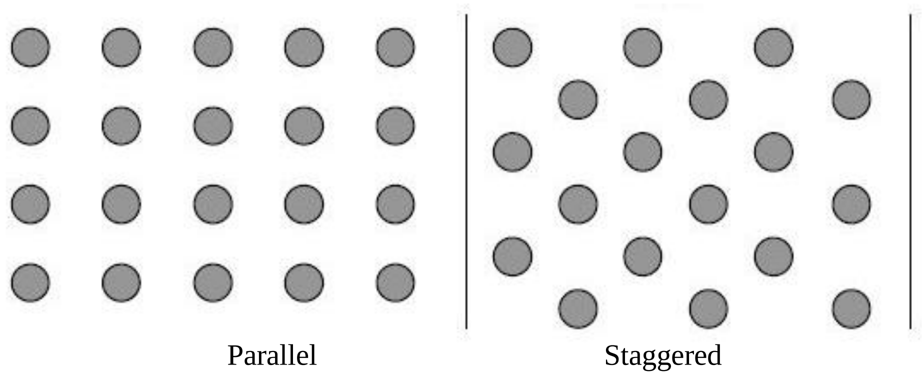

Fig. 3.3 Common planting patterns of vegetation

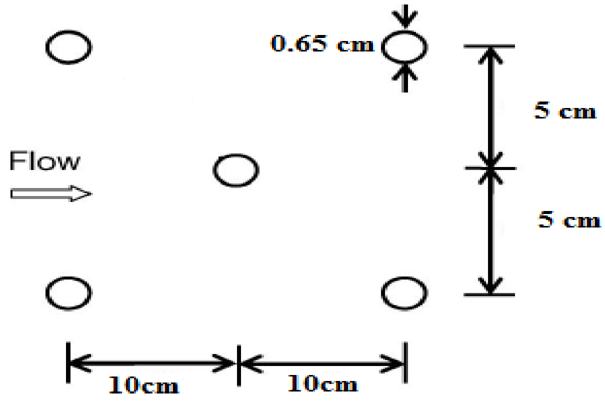

Fig. 3.4 Plan view of the simulated vegetation pattern

3.4. Experimental Procedure

3.4.1 Apparatus and Methodology

Main parameters to be measured during the present experiment are discharge, bed slope, depth of flow and the velocity of flow. The measurement procedure of these parameters is briefly described as follows. Depth of flow in the channel is measured using a point gauge fitted to the travelling bridge operated manually having least count of 0.1 mm. Point velocities are measured using a 16-MHz Micro ADV (Acoustic Doppler Velocity-meter) at a number of locations across the pre-defined channel section. Guide rails are provided at the top of the experimental flume on which a travelling bridge is moved in the longitudinal direction of the entire experimental channel. The point gauge attached to the travelling bridge can also move in both longitudinal and the transverse direction of the experimental channel. The Micro ADV holder is also attached to the bridge on the other side of the point gauge. The micro ADV readings are recorded in a computer placed beside the bridge. As the ADV is unable to read the data from the uppermost layer (up to 5 cm from free surface), a Micro-Pitot tube of 4.77 mm external diameter in conjunction with suitable inclined manometer is used to measure velocity. The Pitot tube is physically rotated normal to the main stream direction till it gives maximum deflection of manometer reading.

Fig. 3.5 Photographs of experimental arrangement (a) Point gauge (b) ADV holder (c) Head gate (d) Tail gate (e) Piezometer (f) ADV

Discharge in the channel is measured by the time rise method. The water flowing out at the downstream end of the experimental channel is led to a volumetric tank of area 20.866 m^2. The change in the depth of water with time is measured by a stopwatch in a glass tube indicator with a scale having least count of 0.01 mm.

A hand-operated tailgate weir is constructed at the downstream end of the channel to regulate and maintain the desired depth of flow in the flume. The bed slope is set by adjusting the whole structure, tilting it upwards or downwards with the help of a lever, which is termed as slope changing lever. Details of the measurement techniques of different parameters are as described below.

3.4.2. Calculation of Bed Slope

To find out the channel bed slope, the tailgate of the flume was closed. The channel was pounded with water. The depth of water at the two end points along the centreline of test reach was measured with the help of a point gauge having least count of 0.1 mm. The point gauge was attached to the travelling bridge, with which the point gauge was able to move in transverse as well as in longitudinal direction of the channel. The slope of the bed was found out by dividing the difference in depth of water at two ends of the test reach by the test length. From the measurement, the bed slope was found out 0.00064 (0.064%) and was kept constant for all runs under both un-submerged and submerged conditions.

3.4.3. Discharge Measurement

A volumetric tank located at the end of channel receives water flowing through the channels. Depending on the flow rate, the time of collection of water in the volumetric tank gets varied; lower value of time will be indicating higher rate of discharge. The collecting time is recorded using a stopwatch. Change in the mean water level in the tank over the time interval is recorded. From the knowledge of the volume of water collected in the measuring tank and the corresponding time of collection, the discharge flowing in the experimental channel for each run is obtained. Simultaneously, the depth of water flowing in the channel is also measured by the point gauge. This depth of flow is termed as gauge or stage. In the next step, the depth of water in the channel is changed and for this new depth of flow/stage/gauge, the discharge flowing over the channel section is measured as described above. In this way a set of data of stage and discharge are collected and then the data are used to develop a stage-discharge relationship. This stage-discharge relationship is helpful in computation of discharge in the channel at different flow depths for the present study.

3.4.4 Measurement of Velocity using ADV:

A 16-MHz Micro ADV (Acoustic Doppler Velocimeter) manufactured by M/s Son Tek, San Diego, Canada is used for velocity measurement. The higher acoustical frequency of 16 MHz makes the Micro-ADV the optimal instrument for laboratory study. The Micro ADV with the software package is used for taking high-quality velocity data at different points. The data is received at the ADV-processor. A computer attached with the processor shows the velocity data after compiling with the software package. At every point, the instrument records a number of velocity data per minute. With the statistical analysis using the installed software, mean values of point velocities are recorded for each flow depth. The Micro-ADV uses the Doppler shift principle to measure the velocity of small particles, assuming to be moving at velocities similar to the fluid. Velocities are measured at 5 cm below the sensor head, minimizing interference of the flow field, and allowing measurements to be made close to the bed.

The Micro ADV has excellent features such as:

- High sampling rates - up to 50 Hz
- Small sampling volume - less than 0.1 cm^3
- Distance to Sampling Volume-5 cm

- ❈ Small optimal scatterer - excellent for low flows
- ❈ High accuracy upto1% of measured range
- ❈ Large velocity ranges between 1 mm/s to 2.5 m/s
- ❈ Excellent low-flow performance
- ❈ No recalibration needed
- ❈ Comprehensive software

Although the 16-MHz Micro ADV is an ideal laboratory instrument used for flow and turbulence studies yet it has the limitations that it is unable to read the upper layer velocity, that is, up to 50 mm from free surface. To overcome this problem, a standard Prandtl type micro-Pitot tube in conjunction with a manometer of accuracy 0.12 mm is used for the measurement of point velocity readings at the specified location for the upper 50 mm region from free surface across the channel.

Fig. 3.6 Photographs during experimental runs (a) Submerged flow (b) Emergent flow (c) ADV readings in computer (d) Overall setup of ADV

3.4.5. Measurement of Velocity using Micro-Pitot Tube

A micro-pitot tube of external diameter 4.77 mm in conjunction with a suitable interval manometer was used to measure velocity. The Pitot tube is fixed to a main scale having vernier scale with least count of 0.1 mm. The main whole of the Pitot tube is faced to the flow direction to give total pressure while the surface holes of the Pitot tube gives static pressure. Both the pressures are seen as heights of water in two limbs of inclined manometer. The difference in water elevation gives the velocity at the particular point (U) where the Pitot tube was mounted and also the pressure difference (Δp) by using the following Bernoulli equations (White, 1999).

$$U = \sqrt{2g\Delta h \, sin\theta} \tag{3.1}$$

$$\Delta p = \rho g \Delta h \sin\theta \tag{3.2}$$

where g is the acceleration due to gravity, ρ is the density of water, Δh is the difference in water elevation in the manometer, θ is the angle of manometer with horizontal base.

While taking velocity readings using Pitot tube, the tube is placed facing the direction of flow and then is rotated along a plane parallel to the bed, till it registers relatively a maximum head difference in the attached manometer. The total head h read by the Pitot tube at the location in the channel is used to give the magnitude of the total velocity vector as $U = \sqrt{2gh\sin\theta}$ where g is the acceleration due to gravity. While doing so, the tube coefficient is taken as unit and the error due to turbulence in the computation of U is considered negligible. Using the data of velocities measured by Pitot tube and micro-ADV, the longitudinal velocity profiles of both submerged and emergent cases are studied and the velocity data are used to evaluate the various hydraulic characteristics of vegetated open channel.

In the present study, all measurements were carried out under uniform flow condition by regulating the out flow through downstream tailgate. Experiments were conducted under two different flow conditions, i.e., submerged and emergent condition and total of five depths under emergent flow condition and six depths under submerged flow condition were taken. Fig. 3.7 shows the flow under submerged condition whereas Fig. 3.8 shows the flow under emergent condition.

Fig. 3.7 Flow under submerged condition

Fig. 3.8 Flow under emergent condition

CHAPTER 4

THEORETICAL CONSIDERATIONS

4.1 General

A large number of researchers have carried out research on resistance characteristics of flows in open channel. Many empirical formulae have already been developed and are now in use. But not a large numbers of works have been done on flow resistance in relatively smooth boundaries of open channel roughened with large roughness elements. Studies on flow resistance caused due to bed forms, vegetation etc. in an open channel flow is helpful to the hydraulic engineers in stage-discharge computation in a channel section, design of channels, sediment analysis etc. Amongst a large number of elements used to roughen the channel sections, vegetation plays a crucial role. Both natural and artificial vegetation can be used in open channel and the channel is called a vegetated channel. Vegetation or grasses of different varieties which are mainly used in soil and water conservation works are either planted in the beds of the open channels or they are naturally grown in the open channels. Naturally occurring vegetation varies both in its distribution density and in geometric characteristics. At times, artificial vegetation like polystyrene strips, polyethylene rigid plastic strips (Kouwen et al., 1969), flexible plastic strips (Nehal and Ming, 2005), thin wire rods (Fenzl, 1962), aluminium alloy wires (Wessels and Strelkoff, 1968), horse hair (Shen and Chow, 1999) and wooden circular dowels (Stone and Shen, 2002) are used to simulate vegetation in open channels. Rigid cylinders of circular cross section are also used to simulate plant stems in laboratory studies (Li and Shen, 1973; Tollner et al., 1982; Jadhav and Buchberger, 1995; Lopez and Gracia, 2001). In the present study, cylindrical iron rods of diameter 6.5 mm are used to simulate vegetation in the open channel.

4.2. Flow Resistance

4.2.1. Drag Coefficient

When water moves through vegetation, drag is produced. The drag creates velocity gradients and eddies that cause momentum loss. These losses are significant for vegetated channels with high density and for wide range of flow conditions. The existing techniques do not consider all these flow conditions in prediction of resistance and so the computed flow resistance is either under-estimated or over-estimated. Vegetative drag has a pronounced effect on flow velocities and thus it affects the flow resistance and therefore any flow expressions in vegetated open channel must consider this drag. Let us consider a steady, uniform, open channel flow with submerged cylindrical stems of equal length distributed uniformly over the channel bed as shown in Fig. 4.1.

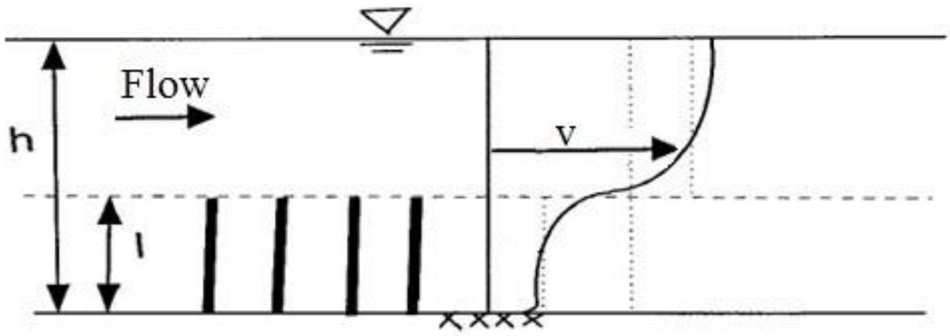

Fig. 4.1 Definition sketch of flow over submerged vegetation (Stone and Shen, 2002)

Applying the momentum balance equation to a control volume of unit bed area of the channel extending from the bed to top of water surface in the channel in streamwise direction, the following relationship is developed.

$$\tau_W = \tau_v + \tau_b \quad (4.1)$$

where τ_W = component of weight of water mass in streamwise direction, τ_v = resistance offered by the drag near the cylinders in stem layer, and τ_b = shear stress of bed.

The component of weight of water in streamwise direction per unit bed area is given by:

$$\tau_w = \rho g S h(1 - \lambda l^*) \quad (4.2)$$

where S = channel slope, h = flow depth, λ = stem area concentration and l^* = ratio of wetted stem length, l to flow depth, h. Under emergent flow condition which is also called protruding condition, the value of l^* equals 1.0 and under submerged condition, it is less than 1.0. Even when the flow just touches the top layer of the vegetation, l^* equals 1.0.

In Eq. 4.2, the term λl^* refers to the fraction of the control volume occupied by vegetation/stem. If an open channel flow without vegetation is considered, then the Eq. (4.2) reduces to $\tau_w = \rho g S h$ which represents the component of weight of water mass in streamwise direction per unit bed area for open channel without any vegetation.

The fraction of bed area covered by the stems is referred to as the area concentration, λ which is expressed as

$$\lambda = \frac{N\pi d^2}{4} \tag{4.3}$$

where N is the number of stems per unit bed area, and d is the diameter of stem.

The drag force in the stem layer per unit bed area is given by:

$$\tau_w = \frac{(\rho C_D N d l V_c{}^2)}{2} \tag{4.4}$$

where C_D = drag coefficient for one cylinder in an array of group of similar cylinders and V_c = maximum depth averaged velocity which is the velocity in the constricted section in stem layer.

As suggested by Stone and Shen (2002), in Eq. 4.4, drag force is determined by maximum depth averaged velocity in stem layer, V_c which is related to mean velocity in vegetation layer, V_l. Mean velocity in vegetation layer V_l is defined as the ratio of discharge, Q in stem layer to cross sectional area, Bl where B is width of channel and l is the height of flow in the channel. The depth averaged velocity, V_c occurs in the constricted section in the vegetation layer as shown in Fig. 4.2.

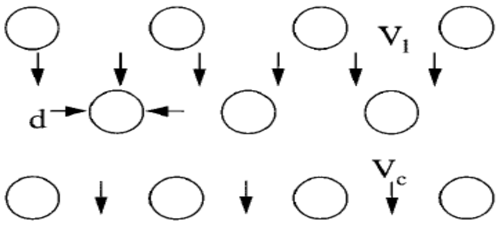

Fig. 4.2 Definition of V_c and V_l as shown in the top view of the vegetation layer (Stone and Shen, 2002)

The two velocities V_c and V_l are related (using control volume concept) as $V_l B = V_c B_c$ where B_c is the constricted flow width of the channel being related to B as $B_c = B\left(1 - d\sqrt{N}\right)$. Hence, V_c and V_l are related as:

$$V_l = V_c\left(1 - d\sqrt{N}\right) \tag{4.5}$$

Using Eq. 4.3 and 4.5, and simplifying, the following equation is developed.

$$V_l = V_c\left(1 - \sqrt{\frac{4\,\lambda}{\pi}}\right) \tag{4.6}$$

It is seen from Eq. 4.6 that the velocity V_c is more than the velocity V_l by a term equals to $\left(\sqrt{\frac{4\,\lambda}{\pi}}\right)$. For no vegetation condition, $\lambda = 0$ and so $V_c = V_l$ (open channel case).

In the present study, 76 stems are planted in unit bed area of channels and the diameter of each stem is 6.5 mm. Hence the value of λ is computed as 0.002522 i.e., 0.2522%. The value of $\lambda = 0.002522$ is kept constant for all the experimental runs.

The bed friction per unit area is determined by

$$\tau_b = \frac{\rho V_l^2 f_b}{8}(1-\lambda) = \frac{\rho g}{C_b^2} V_l^2 (1-\lambda) \tag{4.7}$$

where f_b = friction factor in channel bed, C_b = Chezy's coefficient of channel bed and other terms are defined earlier. In Eq. 4.7, the wake effect is very small since the rod is cylindrical having smooth edging affect. However, for cubical rods, the wake effect behind the rod is to be considered in computation of λ and hence in computation of bed friction factor in channel. Using Moody diagram along with relative roughness, e_b and Reynolds Number, Re, friction factor f can be found.

Usually the stem resistance is so high that the bed friction's effect becomes insignificant. Based on Eq. 4.2 to Eq. 4.7, Eq. 4.8 is written as:

$$V_l^2\left[\frac{f_b(1-\lambda)}{g}+\frac{2\lambda l C_D}{\pi d\left(1-\sqrt{\frac{4\lambda}{\pi}}\right)^2}\right]=gSh(1-\lambda l^*) \tag{4.8}$$

Eq. 4.8 shows that friction/energy slope of flow in the channel (*S*) includes contributions from both stem resistance, S_v and bed resistance, S_b i.e., $S = S_v + S_b$ where

$$S_b = \frac{f_b(1-\lambda)V_l^2}{8gh(1-\lambda l^*)} \tag{4.9}$$

$$S_v = \frac{2C_D\lambda l^* V_l^2}{\pi\left(1-\sqrt{\frac{4\lambda}{\pi}}\right)^2 gd(1-\lambda l^*)} \tag{4.10}$$

Eq. 4.8 can be rearranged and written as

$$V_l = \sqrt{\frac{g(1-\lambda l^*)}{\frac{f_b(1-\lambda)}{8}+\left[\frac{2\lambda l^* h C_D}{\pi d\left(1-\sqrt{\frac{4\lambda}{\pi}}\right)^2}\right]}}\sqrt{hS} \tag{4.11}$$

Since in most of the practical cases, the effect of bed friction is insignificant compared to stem resistance (Stone and Shen, 2002), it is neglected. Using this concept, Eq. 4.11 is simplified as:

$$V_l = \left(1-\sqrt{\frac{4\lambda}{\pi}}\right)\sqrt{\frac{g(1-\lambda l^*)\pi d}{2\lambda l^* C_D}}\sqrt{S} \tag{4.12}$$

Neglecting bed resistance and simplifying Eq. 4.10, the stem layer velocity (V_l) is obtained same as above Eq. 4.12. Using Eq. 4.6, Eq. 4.12 reduces to

$$V_c = \sqrt{\frac{g(1-\lambda l^*)\pi d}{2\lambda l^* C_D}}\sqrt{S} \tag{4.13}$$

where *S* = bed slope of the channel.

Eq. 4.13 is rearranged to give the stem resistance or vegetal drag coefficient or simply called drag coefficient (C_D) as:

$$C_D = \frac{g\left(1-\lambda\, l^*\right)\pi\, d\, S}{2\,\lambda\, l^*\, V_c^{\,2}} \tag{4.14}$$

Eq. 4.12 is used for computation of flow velocity inside stem/vegetation layer. For the emergent flow condition, the value of l^* = 1.0 and the stem layer velocity is independent of flow depth, *h*. But for submerged flow case, l^* < 1.0, and is a variable factor depending on the flow depth, *h* and hence the stem layer velocity is dependent on flow depth, *h*.

In the present experimental study, Eq. 4.14 has been used to compute the drag coefficient for both emergent and submerged flow cases. For various flow depths and discharges keeping the channel bed slope, diameter and spacing of the stem and vegetation density (i.e., stem area concentration, λ), maximum depth averaged flow velocity were measured using Eq. 4.15 and Eq. 4.14 was used to estimate the value of drag coefficient. The depth averaged velocity is computed by the formula:

$$V_c = \frac{1}{h}\left(\sum_{0}^{h} v \cdot dh\right) \tag{4.15}$$

where V_c = average velocity in the constricted section with vegetation as discussed earlier, *h* = flow depth in vegetated channel, *v* = velocity at any point in the vertical plane of the flow and *dh* = distance between two consecutive points in the vertical direction where velocity, *v*, is measured. The flow depth, *h*, is the actual flow depth in submerged flow case and is equal to wetted stem length of the vegetation (*l*) for emergent case. For example, if the flow is under emergent condition and the depth of flow is 7.5 cm then *l* = 7.5 cm. Similarly if the flow is under submerged case and the depth of flow is 12.5 cm, then *l* = 10 cm (which is the height of the vegetation).

4.2.2. Drag Coefficient by Cheng and Nguyen (2011)

Cheng and Nguyen (2011) have proposed a formula (i.e., Eq. 4.16) to compute drag coefficient in vegetated open channel under emergent flow case. Their formula takes into account the side and bed wall corrections in the vegetated channel. The formula is:

$$C_D = \frac{130}{r_v^{\ *}} + 0.8\left[1 - e^{\left(-\frac{r_v^{\ *}}{400}\right)}\right] \qquad (4.16)$$

where $r_v^{\ *}$ = dimensionless vegetation related hydraulic radius defined as:

$$r_v^* = \left(\frac{gS}{\nu^2}\right)^{\frac{1}{3}} r_{vm} \qquad (4.17)$$

where, g = acceleration due to gravity, S = channel bed slope, ν = kinematic viscosity of fluid and r_{vm} = corrected vegetation related hydraulic radius (with bed and side wall correction) which is defined as:

$$r_{vm} = r_v\left[1 - \left(\frac{f_w}{0.5B(1-\lambda)} + \frac{f_b}{h}\right)\frac{r}{f}\right] \qquad (4.18)$$

where, f_w = side wall friction factor, f_b = bed friction factor, h = depth of flow, B = channel width, λ = vegetation density, r_v = vegetation related hydraulic radius, r = hydraulic radius and f = friction factor.

Friction factor, f is given as:

$$f = 8grS/V_c^2 \qquad (4.19)$$

where, r = hydraulic radius and V_c = maximum depth averaged velocity given by Eq. 4.15

Hydraulic radius, r of Eq. 4.19 is given as:

$$r = \left(\frac{1}{h} + \frac{1}{0.5\,B\,(1-\lambda)} + \frac{1}{r_v}\right)^{-1} \qquad (4.20)$$

In Eq. 4.20, the term r_v = vegetation related hydraulic radius which is given as:

$$r_v = \frac{\pi\, d\,(1-\lambda)}{4\lambda} \tag{4.21}$$

In Eq. 4.21, d = diameter of the cylindrical iron rod i.e. 6.5 mm and λ = vegetation density i.e. 0.0025 as considered for the present experiment.

If an open channel without any vegetation is considered then, λ = 0 and Eq. 4.20 reduces to hydraulic radius for rectangular open channel flow, $r = \dfrac{B\,h}{B + 2\,h}$.

Evaluation of the parameters f_w and f_b is done by considering the explicit formula (Cheng and Nguyen, 2011) as:

$$f_w^{\ \alpha} = f_{wS}^{\ \alpha} + f_{wR}^{\ \alpha} \tag{4.22}$$

In which

$$f_{wS} = 31\left[\ln\left(1.3\,\frac{R}{f}\right)\right]^{-2.7} \tag{4.23}$$

$$f_{wR} = 11.7\left[\ln\left(7.6\,\frac{4\,r}{f\,k_{sw}}\right)\right]^{-2.5} \tag{4.24}$$

And $\alpha = 2\left(\dfrac{4\,r}{f\,k_{sw}}\right)^{0.1}$ (4.25)

As suggested by Cheng and Nguyen (2011) in Eq. 4.22 to Eq. 4.25, Reynolds Number, R is given as $4rV_c/v$ where r is defined by Eq. 4.20, k_{sw} = equivalent wall roughness height which is assumed in this experiment as 0.37 mm. Eq. 4.22 to 4.25 are solved to find out the value of f_w.

In the similar way Eq. 4.22 to Eq. 4.25 are solved by replacing the subscript '*w*' with '*b*' and assuming k_{sb} = equivalent bed roughness height which is assumed in this experiment same as k_{sw} i.e. 0.37 mm.

4.2.3. Drag Coefficient by Kothyari (2009)

Kothyari et al. (2009) carried out a series of laboratory experiments for determination of the stem drag with tall emergent stiff simulated vegetation. Based on their results as well as the results of other investigators, the following equation was proposed by Kothyari et al. (2009) to predict the vegetal drag coefficient of a single cylindrical stem placed in a group of array of identical stems in subcritical and supercritical flows.

$$C_D = 1.8\xi \,\mathrm{Re}^{\frac{-3}{50}}\left[1 + 0.45\ln(1 + 100\lambda)\right]\left(0.8 + 0.2Fr - 0.15Fr^2\right) \tag{4.26}$$

where ξ is a parameter representing the stem (cylinder) staggering pattern, with $\xi = 1.0$ for the regular triangular staggering stem pattern and 0.8 for regular square staggering pattern, λ = area concentration of stems, $Re = (V_c d)/v$ is stem Reynolds Number with v being the kinematic viscosity of the fluid and d = diameter of cylindrical rod and $Fr = V_c/(gh)^{1/2}$ is flow Froude Number. In the present experiment, vegetation are arranged in triangular staggered pattern and hence ξ is taken as 1.0 for determination of C_D.

4.3. Manning's Roughness Coefficient

Distribution of energy in a channel section is an important aspect that needs to be addressed properly. An important hydraulic property of a channel is its influence on flow velocity. This property is often characterised by Manning's roughness coefficient *n* which is also called retardance coefficient. While using Manning's equation, selection of a suitable value of *n* is the single most important parameter for the proper estimation of velocity in an open channel. Major factors affecting Manning's roughness coefficient are the (i) surface roughness, (ii) vegetation, (iii) channel irregularity, (iv) channel alignment, (v) silting and scouring, (vi) shape and size of a channel, and (vii) stage-discharge relationship. Assuming the flow to be uniform and neglecting all non-frictional losses, the energy gradient can be considered equal to the average longitudinal bed slope *S* of a channel. Under steady and uniform flow conditions, Manning's roughness coefficient can be determined from the velocity of flow, channel bed slope and regular open channel hydraulic radius, R by the formula

$$V_c = \frac{1}{n} R^{2/3} \sqrt{S} \tag{4.27}$$

where, V_c = maximum depth averaged velocity in the entire section of flow depth of channel (also called here the mean channel flow velocity), and R = regular open channel hydraulic radius calculated based on the entire section of flow depth of channel. Value of R is given as

$$R = \frac{B\,h}{B + 2\,h} \tag{4.28}$$

Using Eq. 4.27 and Eq. 4.28, Manning's n is computed as:

$$n = \frac{\sqrt{S}}{V_c}\left(\frac{B\,h}{B + 2h}\right)^{2/3} \tag{4.29}$$

Cheng and Nguyen (2011) have proposed a model to estimate Manning's n for vegetated waterway under emergent condition. This model is derived below:

Considering Eq. 4.14

$$C_D = \frac{g\left(1 - \lambda\, l^*\right)\pi\, d\, S}{2\,\lambda\, l^*\, V_c^2}$$

For emergent case, the value of l^* = 1 and the above equation is reduced to

$$C_D = \frac{g\left(1 - \lambda\right)\pi\, d\, S}{2\,\lambda\, V_c^2} \tag{4.30}$$

Rearranging Eq. 4.30 we get

$$\frac{\sqrt{S}}{V_c} = \left(\frac{2\,\lambda\, C_D}{g\,\left((1 - \lambda)\,\pi\, d\,\right)}\right)^{1/2} \tag{4.31}$$

Simplifying Eq. 4.21 we get

$$\frac{2\lambda}{\left(1 - \lambda\right)\pi\, d} = \frac{1}{2\, r_v} \tag{4.32}$$

Using Eq. 4.32 and Eq. 4.31

$$\frac{\sqrt{S}}{V_c} = \left(\frac{C_D}{2\, g\, r_v} \right)^{1/2} \tag{4.33}$$

Using Eq. 4.33 and 4.29 Manning's *n* is given as:

$$n = \sqrt{\frac{C_D}{2\, g\, r_v}} \left(\frac{B\, h}{B + 2\, h} \right)^{2/3} \tag{4.34}$$

When bed and side wall correction is considered, the term r_v in Eq. 4.34 changes to r_{vm} Eq. 4.18 in computation of Manning's *n.* In Eq. 4.34, Manning's *n* is computed by considering the estimated value of C_D with Eq. 4.16 as proposed by Cheng and Nguyen (2011) following Eq. 4.16 to Eq. 4.25.

4.4. Friction Factor

Friction factor is another important resistance parameter that affects flow in an open channel. An incomplete understanding of friction coefficient for rough surfaces is one of the limiting factors in the application of basic momentum and continuity equations to the modeling of overland flow. Many authors including Phelps (1970) and Chen (1976) have supported the importance of friction factors in the field of open channel flow. ASCE Task Force (1963) has also recommended the use of this parameter in all aspects of engineering studies including Hydraulics.

The factors that affect Manning's *n* also affect friction factor. The main factors that affect the friction factor are surface roughness, channel irregularity, channel alignment including meandering and vegetation characteristics. The influencing vegetation characteristics are height, thickness, density and planting geometry of vegetation. Submergence ratio of vegetation too decides the magnitude of friction factor. Various flow parameters including discharge, depth of flow and channel slope also influence the friction factor in open channel flow.

As reported by Einstein and Barbarosa (1952) and Taylor and Brooks (1962) and supported by Lovera and Kennedy (1969), friction factor in open channels consist of two terms: (i) friction factor due to sand grain roughness and (ii) friction factor due to bed forms, channel irregularities and sediment load. The total friction factor is the sum of these two friction factors.

Friction factor due to sand grain roughness (f') is given as:

$$f' = \frac{8\,g\,RS'_f}{V_c^{\,2}} \tag{4.35}$$

Friction factor due to form roughness (f'') is given as:

$$f'' = \frac{8\,g\;R\;S''_f}{V_c^{\,2}} \tag{4.36}$$

where, S'_f = energy slope associated with soil boundary and S''_f is energy slope associated with drags on vegetated elements.

Total energy slope, S_f is given by

$$S_f = S'_f + S''_f \tag{4.37}$$

and total friction factor, f is expressed as:

$$f = f' + f'' \tag{4.38}$$

Using Eq. 4.35 to 4.38 and simplifying, friction factor is given as under.

$$f = \frac{8\;g\;R\;S_f}{V_c^{\,2}} \tag{4.39a}$$

Considering uniform open channel flow, energy slope becomes channel bed slope and then f is given as

$$f = \frac{8\;g\;R\;S}{V_c^{\,2}} \tag{4.39b}$$

In Eq. 4.39(b), friction factor f is also called Darcy-Weisbach friction factor, f.

Parameter R of Eq. 4.39 (b) is regular open channel hydraulic radius calculated based on the entire section of flow depth of channel and is defined by Eq. 4.28 and V_c is the maximum depth averaged velocity calculated based on entire section of flow depth.

Darcy-Weisbach friction factor, f can also be deduced from Eq. 4.11. Considering a limiting case of open channel without any vegetation i.e., with vegetation density, $\lambda = 0$, Eq. 4.11 deduces to the familiar Darcy Weisbach formula $V_c = \left(\sqrt{8g/f_b}\right)\sqrt{hS}$ where f_b is bed friction. Considering a wide channel section, the total friction, f in the whole section is obtained by Eq. 4.39(b) where h is replaced by hydraulic radius, R.

The relationship between the Darcy-Weisbach friction factor, f and Manning's roughness coefficient, n can be shown as:

$$n = R^{1/6}\sqrt{\frac{f}{8g}} \tag{4.40}$$

4.5. Other Hydraulic Parameters

4.5.1. Chezy's Coefficient

Like Manning's roughness coefficient, n, Chezy's coefficient, C is another important hydraulic parameter in open channel flow. The flow velocity by Chezy's equation is given as:

$$V_c = C\sqrt{RS} \tag{4.41}$$

Rearranging the terms of Eq. 4.41, Chezy's coefficient, C *is* obtained as

$$C = \frac{V_c}{\sqrt{RS}} \tag{4.42}$$

4.5.2. Reynolds Number

Reynolds Number is an often used flow parameter in various fields of hydraulic study. It decides whether the flow is laminar or turbulent. It is the ratio of inertia force to viscous force. Many investigators have related drag coefficient with Reynolds Number and have found interesting relationships. However, the definition of Reynolds Number varies in literature which involves various lengths and velocity scales. By ignoring variations in the vegetation characteristics, some researchers have simply used flow depth in the definition of Reynolds Number (Wu et al., 1999). Some other investigators have considered stem diameter, d whereas others have considered stem spacing, s as a parameter in the computation of Reynolds Number. Table 4.1 illustrates various definitions of Reynolds Number for open channel flows subjected to emergent flow conditions (Cheng and Nguyen, 2011).

Table 4.1 Definitions of Reynolds Number subjected to emergent flows

Investigators	Reynolds Number	Characteristic velocity	Characteristic length	Remarks
Wu et al. (1999)	$V h / v$	Bulk velocity, V	Flow depth, h	$V = Q / B h$
Ishikawa et al. (2000)	$V d / v$	Bulk velocity, V	Stem diameter, d	
Lee et al. (2004)	$V h / v$, $V s / v$, $V d / v$	Bulk velocity, V	Flow depth, h ; Stem diameter, d ; Stem spacing, s	
Tanino and Nepf (2008)	$V_c d / v$	Maximum depth averaged velocity	Stem diameter, d	
Kothyari et al. (2009)	$V_c d / v$	Maximum depth averaged velocity	Stem diameter, d	
Cheng and Nguyen (2011)	$V_c r_v / v$	Maximum depth averaged velocity	Vegetation related hydraulic radius, r_v	r_v as given by Eq. 4.21

In the present study, Reynolds Number, Re is estimated by the formula:

$$\mathrm{Re} = \frac{\rho V_c R}{\mu} \text{ and } \mathrm{Re} = \frac{V_c R}{v} \tag{4.43}$$

where, R = hydraulic radius for the entire flow section considering entire flow depth, h and is given by Eq. 4.28, μ = dynamic viscosity, v = kinematic viscosity ($v = \mu/\rho$), ρ = density of water. Value of $v = 10^{-6}$ m^2/s. The term V_c in Eq. 4.43 is computed for entire flow depth in the channel by Eq. 4.15.

4.5.3. Froude Number

Froude Number decides whether a flow in open channel is either sub-critical or critical or super-critical. If the value of Froude Number is < 1, then flow is said to be sub-critical, if it is = 1, then flow is critical and for super-critical flow, if its value >1. Generally for a vegetated open channel flow with smaller bed slope of the channel, velocity of flow is very less and value Froude Number is less than 1 indicating that the flow in under sub-critical condition. As the vegetation density increases, the value of Froude Number decreases. But with lesser vegetation density, increased bed slope and higher depth of flow cases, Froude Number may be more than 1.0 revealing the flow to be super-critical.

Value of Froude Number, *Fr* is expressed as

$$Fr = \frac{V_c}{\sqrt{g\,h}} \tag{4.44}$$

4.5.4. Submergence Ratio

Submergence ratio in a vegetated channel is referred as the ratio of wetted stem length (l) to the depth of flow of water in the channel (h). This ratio, $l^* = l/h$, is 1.0 for the emergent (i.e., protruding) condition. For the submerged condition, l^* is less than 1.0. Under emergent case when the depth of flow is less than the height of vegetation, values of l and h become same and so the ratio (l^*) is 1.0. However, under submerged case, $h > l$ and so the value of $l^* < 1.0$.

4.5.5. Aspect Ratio

Aspect ratio of a channel is the ratio of width of the channel section to the depth of flow in the section. It is given as B/h where B = width of channel section (0.60 m in the present experiment) and h = depth of flow in the channel section which varies with slope and discharge in channel.

4.6. Velocity Distribution in Vegetated Open Channels

4.6.1. Conceptual Background

Determination of flow within a vegetated open channel is a very complicated problem. This problem becomes more complicated when the boundary roughness changes from time to time with the stage of growth of vegetation. For a channel lined with natural vegetation or simulated vegetation having less flexural stiffness like horse-hair or flexible plastic strips etc., there exist three basic regimes of flow. They are:

- Erect: When the vegetation is not deflected (it occurs when depth of flow is less)
- Waving motion: With increased depth of flow, when vegetation undergoes waving with the tips of vegetation being deflected from its upright position and
- Prone condition: When the vegetation undergoes submergence with higher depth of flow as a result of varying velocity profiles: velocity through vegetation and velocity above vegetation.

Velocity through vegetation is almost constant at every longitudinal coordinate along the flow path up to a height of deflected vegetation height. Above the deflected vegetation, velocity of water increases rapidly and follows logarithmic law. General velocity profile of a natural vegetated open channel under submergence case is shown in Fig. 4.3. In the Fig. 4.3, k = deflected vegetation height, V_k = constant velocity within vegetation, v = velocity above vegetation at any longitudinal distance y above the channel bed and D = depth of flow.

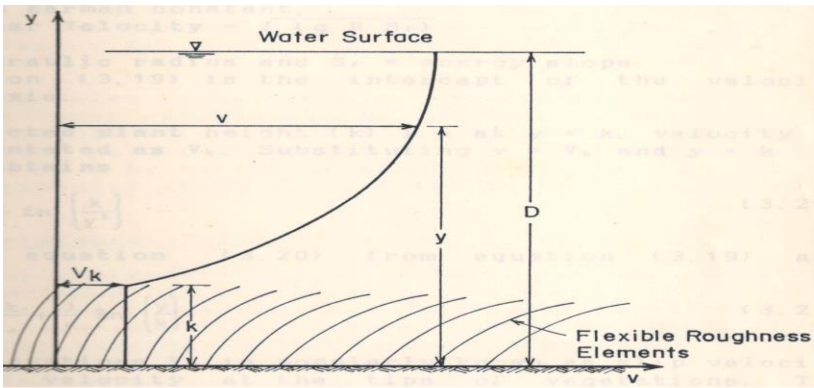

Fig. 4.3 General velocity profile in a natural vegetated open channel (Panigrahi, 1987)

In case of simulated rigid vegetation such as cylindrical iron rods which are considered in the present study, there is no waving motion in velocity profile. There are two basic regimes of flow. When the depth of flow is less than the vegetation height, flow is said to be under emergent case/protruding case. With increasing depth of flow when the submergence of vegetation occurs, the flow is said to be under submergence case. These two types of flow regimes are discussed below.

4.6.2. Emergent Flow Case

An open channel flow with vegetation can be divided vertically into two major regions, an inner region which lies vey near to the channel bed and an outer region that lies above it. Both the regions overlap in part. The lower region is the roughness layer or vegetation layer. The near-bed inner region is influenced predominantly by roughness elements. Emergent condition is the limiting condition of submerged condition without surface layer. Generally the flow velocity is always smaller in the vegetation layer in comparison to the surface layer since the former undergoes the drag effect. Laboratory studies (Tsujimoto and Kitamura, 1990) reveal that velocity profile is normally similar along the depths of emergent cases. Bed friction shows its effect on the velocity profile's shape only near the bed where it reduces to zero. The velocity immediately attains a constant value which can be achieved on calculation based on balancing of gravitational force along with the hydrodynamic resistance of the stems. Definition sketch for open channel flow with emergent flow condition is depicted in Fig. 4.4 The presence of submerged vegetation serves as large-scale roughness to obstruct the near-bed flow and thus reduce the flow velocity. If the surface flow becomes very shallow, the roughness sublayer may extend up to the free surface and thus the logarithmic layer would become thinner and might even be absent (Brunet et al., 1994).

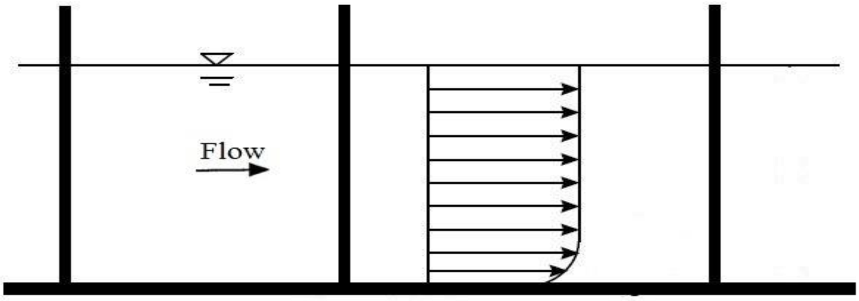

Fig. 4.4 Definition sketch for open channel flow with emergent vegetation (Fairbanks, 1998)

4.6.3. Submerged Flow Case

Open channel flow with submerged cylindrical roughness can be analysed with two interacting flow layers. The lower layer is observed to be the roughness layer or stem layer. The other layer is the surface layer which is above stems and therefore contains no roughness. The depth above the stems is characterized as the surface layer and undergoes significantly greater velocities in comparison to stem layer. Definition sketch of flow over submerged vegetation condition is earlier presented in Fig. 4.1. Because of the mixing behaviour of surface and stem layers, submerged flow condition is more difficult when compared to emergent flow condition. For submerged flow depths, however the stem layer velocity will approach beyond the constant value in reference to the shearing effect in the surface layer. The depth beyond the stem undergoes variations in shearing effect and hence becomes tough to predict. The flow through the near-bed vegetation layer differs from that in the surface layer above. The two-layer stream resembles the plane mixing layer, in that an inflection point appears in the velocity profile, implying that the resultant turbulent flow is inherently unstable but coherent. This analogy suggests that the scaling that underlies the logarithmic law is not applicable for the depth limited, vegetated open channel flows. Unlike the flow over a smooth, impermeable boundary, the vegetated flow invalidates the “no-slip” velocity at the edge of the vegetation, and a point of inflection appears in the velocity profile approximately at the interface of the two streams, as shown in Fig. 4.1. It is also noted that the logarithmic law is theoretically applicable to the inertial sublayer (Hinze, 1975; Kundu et al., 2004; Schlichting, 1979).

However, if the flow depth is reduced, roughness elements may significantly affect the flow upto the free surface. Then, the major portion of the flow above vegetation may be characterized more appropriately as a roughness sublayer than an inertial sublayer where the logarithmic law applies.

4.6.4. Stem/Vegetation Layer Velocity

Average velocity within the stem or vegetation layer can be predicted by the equation

$$V_l = \left(1 - \sqrt{\frac{4\lambda}{\pi}}\right)\sqrt{\frac{g(1-\lambda l^*)\pi d}{2\lambda l^* C_D}}\sqrt{S} \tag{4.45}$$

where all the terms of the equation are defined earlier. In the above equation, value of the drag coefficient, C_D is considered as the average value of C_D for all the experimental runs.

Eq. 4.45 can be used to compute stem or vegetation layer's depth averaged velocity both under emergent and submerged condition. Under emergent case, value of l^*=1. So for a particular experimental setup with a particular value of S, d and λ, Eq. 4.45 gives constant value of V_l for all runs in emergent flow case irrespective of any value of flow depth, h. However, under the submerged case, when the depth of flow changes, values of l^* also changes and hence value of V_l for all runs in submerged flow case changes with depth of flow.

4.6.5. Mean Channel Velocity

For channels without vegetation, average velocity or channel's conveyance capacity can be expressed from flow resistance equations like Darcy-Weisbach, Chezy or Manning's equation. A similar formula may be used for channel with cylindrical roughness. To compute the mean channel velocity in vegetated open channel which is also referred to as the cross sectional averaged velocity, Stone and Shen (2002) have proposed the following formula:

$$V = \frac{(1-dl^*\sqrt{N})}{F_v\sqrt{l^*}}\sqrt{\frac{(1-\lambda l^*)}{\frac{1}{2}C_D}}\sqrt{\frac{g}{Nd}}\sqrt{S} \tag{4.46}$$

where V = mean channel velocity defined as Q/Bh (B is width of flume and h is flow depth), F_v = a velocity coefficient which depends on l^*, N = number of stems per m^2 of bed area which is 76 in the present experiment and other parameters are defined earlier.

From a series of experimental data of vegetated flow both under emergent and submerged cases and also using the flow data of other investigators, Stone and Shen (2002) proposed that value of $F_v = \sqrt{l^*}$

Putting the value of $F_v = \sqrt{l^*}$ in Eq. 4.46, the mean channel velocity under submerged flow case is computed as:

$$V = \frac{\left(1-dl^*\sqrt{N}\right)}{l^*}\sqrt{\frac{\left(1-\lambda l^*\right)}{\frac{1}{2}C_D}}\sqrt{\frac{g}{Nd}}\sqrt{S} \tag{4.47}$$

Under emergent flow case, l^* = 1 and so mean channel velocity is computed as

$$V = \left(1-d\sqrt{N}\right)\sqrt{\frac{(1-\lambda)}{\frac{1}{2}C_D}}\sqrt{\frac{g}{Nd}}\sqrt{S} \tag{4.48}$$

Eq. 4.48 indicates that mean channel velocity in emergent case is independent of flow depth, i.e., cross sectional averaged velocity within the vegetation layer is having a uniform value for all flow depths.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 General

Chapter 3 provides the different experimental procedures including measurement techniques of various data including flow depth (stage), velocity, slope of the channel etc. Theoretical considerations for the evaluation of different hydraulic parameters of the vegetated open channel are discussed in Chapter 4. This chapter presents the results of the various parameters evaluated from the experimental runs and discusses on them.

5.2 Stage-Discharge Variation in Vegetated Open Channel

Discharge is a vital parameter used in the study of hydraulics. Accurate measurement of discharge is of utmost importance since it is frequently used in the evaluation of a number of hydraulic parameters. It is cumbersome to measure discharge always at the beginning of each experimental run. On the other hand, if a relationship between discharge and stage which is otherwise called head/depth is developed, then it will save considerable time in computing discharge instead of measuring it. From the developed relationship, one can compute the discharge if head or depth of water is measured which is relatively easier than measuring the discharge. As discussed in Chapter 3, 22 runs each at 22 different depths of flow were carried out in the rectangular hydraulic flume with vegetation which is used in the present experimental study under uniform flow conditions. Relationship between these discharges and their stages (i.e., heads/depths) were studied. The developed relationship is found to be in the power form with high value of coefficient of determination (R^2 = 0.99). The graphical relationship is presented in Fig. 5.1. The relationship is found as:

$$h = 2.097\, Q^{0.670} \tag{5.1}$$

where, h = head or depth of flow in the channel, m and Q = discharge, m^3/s. In the present experimental study, Eq. 5.1 was used to estimate the discharge flowing in the channel under both emergent and submerged flow conditions using different values of depths of flow, h in the channel. For checking the accuracy, some of the values of the discharges so computed by Eq. 5.1, were compared with the measured values and the results are found to be very much satisfactory with very negligible difference in discharge values.

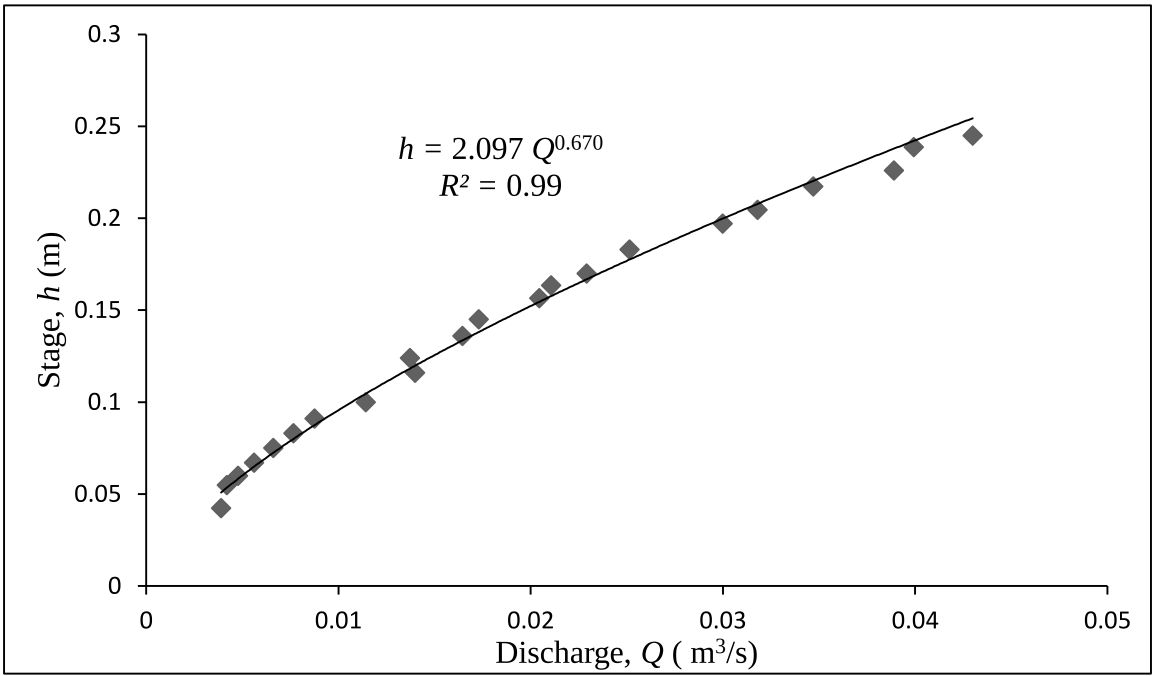

Fig. 5.1. Stage-discharge relationship in vegetated channel

5.3 Ranges of Pertinent Variables and Parameters

In the present study, the pertinent variables and parameters measured/evaluated are discharge, depth of flow, width of channel section, cross sectional area of flow, wetted perimeter, and hydraulic radius, maximum depth average velocity in the constricted vegetated section, aspect ratio and submergence ratio. The above mentioned variables and parameters are measured for both emergent and submerged flow conditions. The values so measured and evaluated are mentioned in Table 5.1. (a) and 5.1 (b) for submerged and emergent flow conditions, respectively. For all the experimental runs, the height, diameter and vegetation concentration area, λ were kept constant and these values were 0.10 m, 0.0065 m and 0.002522, respectively. Moreover a constant bed slope of the channel (0.064%) was used for all the runs. A total of 6 experimental runs for submerged flow condition and 5 experimental runs for emergent flow conditions were taken for the study. As mentioned earlier, because of limited pump capacity, large number of experimental runs with varying discharges and flow depths could not be obtained for the study.

Table 5.1(a) Pertinent variables and parameters for vegetated channel for submerged flow

Discharge Q (m^3/s)	Flow depth h (m)	Channel width B (m)	Cross sectional area A (m^2)	Wetted perimeter P (m)	Hydraulic radius $R=(A/P)$	Mean constricted channel velocity V_c (m/s)	Aspect ratio(B/h)	Submergence ratio (l^*)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0.0137	0.124	0.6	0.0744	0.848	0.087	0.190	4.84	0.806
0.0173	0.145	0.6	0.0870	0.890	0.098	0.215	4.13	0.689
0.0229	0.170	0.6	0.1020	0.940	0.108	0.243	3.52	0.588
0.0230	0.197	0.6	0.1182	0.944	0.119	0.271	3.04	0.507
0.0389	0.226	0.6	0.1356	1.052	0.129	0.303	2.65	0.442
0.0430	0.245	0.6	0.147	1.090	0.135	0.322	2.45	0.408

Table 5.1(b) Pertinent variables and parameters for vegetated channel for emergent flow

Discharge Q (m^3/s)	Flow depth h (m)	Channel width B (m)	Cross sectional area A (m^2)	Wetted perimeter P (m)	Hydraulic radius $R=(A/P)$	Mean constricted channel velocity V_c (m/s)	Aspect ratio(B/h)	Submergence ratio (l^*)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0.0050	0.060	0.6	0.036	0.720	0.050	0.158	10.00	1.0
0.0060	0.067	0.6	0.0402	0.734	0.055	0.156	8.95	1.0
0.0066	0.075	0.6	0.045	0.750	0.060	0.155	8.00	1.0
0.0072	0.083	0.6	0.0498	0.766	0.065	0.154	7.23	1.0
0.0078	0.091	0.6	0.0546	0.782	0.070	0.153	6.59	1.0

In the submerged flow condition, the discharge is varied from 0.0137 to 0.0430 m^3/s and the depth of flow varies from 0.124 m to 0.245 m. Values of maximum depth averaged velocity which is also called mean channel velocity was found to vary from 0.190 to 0.322 m/s (Table 5.1 a). Mean channel velocity of vegetated open channels was found to increase with increasing discharge and depth of flow. Under submerged condition, when the depth of flow increases as compared to the vegetation height, there is less resistance to flow and the flow behaves like an open channel without any vegetation. Consequently, the velocity increases. Similar results have been reported by Panigrahi (1987) who carried on studies in grass lined channel and found out that at larger depth of flow when all the grasses undergo complete deflection and the flow occurs above the deflected plant height, the velocity of flow increases with increasing depth of flow.

In the emergent flow condition, the discharge is varied from 0.005 to 0.0078 m^3/s and the depth of flow varies from 0.06 m to 0.091 m. Mean channel velocity within the stem layer which is the depth averaged velocity in the vegetated or stem layer under emergent case remains almost same for all the depths of flows and the measured values range from 0.153 to 0.158 m/s (Table 5.1 b). Similar results of obtaining a low and constant velocity within the vegetation zone for various depths of flow under emergent condition have been reported by a number of investigators (Panigrahi, 1987; Stone and Shen, 2002; and Cheng and Nguyen, 2011).

5.4. Submergence Ratio

Submergence ratio (l^*) which is the ratio of wetted stem length (l) to the depth of flow (h) varies with depths of flow. For all the experimental runs under submerged case, the value of the wetted stem length (l) is 10 cm which is the height of vegetation/stem. So when the depth of flow increases ($h > l$), the value of submergence ratio decreases. In the present study, values of submergence ratio were found to decrease from 0.806 to 0.408 as the depth of flow increased from 0.124 to 0.245 m (Table 5.1 a). Under emergent flow case, values of wetted stem length are same as the depth of flow and so the submergence ratio is 1.0 for all the experimental runs (Table 5.1 b).

5.5. Aspect Ratio

Aspect ratio is the ratio between the width of flume (B) and the depth of flow (h). The width of flume is 0.60 m. Since the depth of flow in submerged case ranged from 0.124 to 0.245 m, aspect ratio was found to range from 4.834 to 2.445. In emergent case, the depth of flow ranged from 0.06 to 0.067 m, and hence the aspect ratio varies from 10 to 6.593. Under both the submerged as well as emergent flow conditions, the impact of aspect ratio on the coefficient of drag (C_D) and coefficient of roughness n in the experimental channel using rigid cylindrical form of vegetation has been analysed and given in later sections.

5.6. Hydraulic Resistance

5.6.1. Vegetative Drag Coefficient

Vegetation that grow in channels, rivers and other flood plain areas adversely affects the aquatic and biological environments. They increase the flow resistance and thus decrease the discharge in open channels, help in flood attenuation and play an important role in deposition of sediments, nutrients and pollutants. Effect of resistance especially by the drag induced by the stems and foliage also help in study of modelling of soil erosion and rainfall-runoff processes. The stem or vegetation drag coefficient is often used as an important resistance parameter to flow in vegetated open channels (Stone and Shen, 2002; Armanini et al., 2005). The resistance to vegetated open channel flows generally depends on a number of factors including channel geometry, vegetation (i.e., height, thickness, density and their configuration patterns), flow parameters like discharge, depth of flow as well as submergence ratio of the vegetation.

In this study an attempt has been made to evaluate the roughness coefficient n and the vegetation/stem drag coefficient or elsewhere referred in this chapter as drag coefficient under both submerged and emergent flow conditions at various discharges and flow depths. Other parameters including channel geometry, vegetation characteristics etc. are kept constant for all the experimental runs i.e. all the experimental runs were conducted at a particular bed slope of the channel (0.064%), with 10 cm high, 6.5 mm thick rigid vegetation (i.e., iron rods) planted in staggered patterns at a vegetation area concentration of 0.002522. Values of the drag coefficient (C_D) were computed by Eq. 4.14 as discussed in Chapter 4 for both emergent and submerged flow conditions and are given in Table 5.2(a) and Table 5.2(b), respectively. While using Eq. 4.14 for computation of C_D for emergent flow case, value of l^* is taken as 1.0 for all the experimental runs. However, for the submerged case, the value of l^* varies from 0.408 to 0.806 depending on the depths of flow. Total five values of C_D for emergent case and six values of C_D for submerged case are computed and presented in these tables.

Table 5.2(a) Drag coefficient for vegetated channel for submerged flow

Flow depth h (m)	Mean velocity within vegetation layer V_c (m/s)	Submergence ratio, l^*	Values of C_D		
			Actual, C_D (By Eq. (4.14))	C_D by Cheng and Nguyen (2011)	C_D by Kothyari et al. (2009)
(1)	(2)	(3)	(4)	(5)	(6)
0.124	0.184	0.806	0.922	0.955	1.072
0.145	0.194	0.689	0.977	0.958	1.066
0.170	0.201	0.588	1.066	0.963	1.060
0.197	0.214	0.507	1.092	0.967	1.054
0.226	0.227	0.442	1.117	0.974	1.049
0.245	0.229	0.408	1.188	0.978	1.046

Table 5.2(b) Drag coefficient for vegetated channel for emergent flow

Flow depth h (m)	Mean velocity within vegetation layer V_c (m/s)	Submergence ratio, l^*	Values of C_D		
			Actual C_D by Eq. 4.14	C_D by Cheng and Nguyen (2011)	C_D by Kothyari et al. (2009)
(1)	(2)	(3)	(4)	(5)	(6)
0.060	0.158	1.0	1.010	0.973	1.091
0.067	0.156	1.0	1.035	0.965	1.089
0.075	0.155	1.0	1.050	0.959	1.087
0.083	0.154	1.0	1.072	0.955	1.086
0.091	0.153	1.0	1.082	0.951	1.085

It is observed that under submergence condition, as the depth of flow increases, drag coefficient gradually increases. When the depth of flow increases from 0.124 to 0.245 m, values of C_D increases from 0.922 to 1.188. The results are supported by the findings of Stone and Shen (2002) who conducted studies with rigid cylindrical dowels under both submerged and emergent case and observed that as the depth of flow is increased, values of

C_D correspondingly also increased. A value of C_D computed by Cheng and Nguyen (2011) method varies from 0.955 to 0.978 as the depth of flow varies from 0.124 to 0.245 m. The last column of Table 5.2 (a) represents the computed values of C_D by Kothyari et al. (2009) method. As per this method, values of C_D varies from 1.072 to 1.046 as the depth of flow varies from 0.124 to 0.245 m. The average values of C_D for all the experimental runs under submerged case by the actual, Cheng and Nguyen (2011) and Kothyari et al. (2009) methods are found to be 1.060, 0.966 and 1.056, respectively. The absolute percent deviation of the values of C_D computed by the actual and Cheng and Nguyen (2011) method varies from 3.57 to 17.68 with an average value of 9.52%. Similarly the absolute percent deviation of the values of C_D computed by the actual and Kothyari et al. (2009) method varies from 0.56 to 16.27 with an average value of 7.91%. Since the average percent deviation of the C_D values between the above mentioned three methods are very less (less than 10.0%), computation of C_D may be taken as correct.

Under emergent flow condition, as the depth of flow increases, the resistance to flow is found to increase. This is revealed from the fact that as the depth of flow increases from 0.06 to 0.091 m, values of C_D are observed to get increased from 1.010 to 1.082 (Table 5.2 b). An increase of drag coefficient with increase of depth of flow may be caused due to more obstructions of frontal area of vegetation to flow as the depth increases. A similar conclusion has also been drawn by Wu et al. (1999) who conducted experiments using rubberized horse hair matters and found that C_D increased with corresponding increase of flow depth. Using plastic blades to simulate vegetation, Nehal and Ming (2005) also concluded that with increasing depth of flow under emergent flow condition, drag resistance gets increased.

The average values of C_D for all the experimental runs under emergent case by the actual, Cheng and Nguyen (2011) and Kothyari et al. (2009) are found to be 1.050, 0.961 and 1.087, respectively. The absolute percent deviation of the computed C_D values by the actual and

Cheng and Nguyen (2011) method varies from 3.66 to 12.10 with a mean value of only 8.42%. Similarly the absolute percent deviation of the computed C_D values by the actual and Kothyari et al. (2009) method were observed to be 0.28 to 8.02 with a low mean value of 3.67% only. Hence, it may be inferred that computation of C_D for emergent flow case by the different methods are right.

In this study for comparison purposes, values of drag coefficient, C_D, computed by other investigators along with the data of various vegetation area concentrations, thickness, spacing of vegetation and number of stems/vegetation per unit bed area (bed area of 1 m^2) are presented (Table 5.3). In the same table, C_D values computed by the present experiment data using Cheng and Nguyen (2011) and Kothyari et al. (2009) methods are also presented.

Table 5.3 Computation of drag coefficients by various investigators

Investigator	Vegetation area concentration λ, %	Thickness of vegetation, d, cm	Vegetation spacing, s, cm	No. of vegetation/m^2	C_D
Stone and Shen (2002)	6.10%	1.270	4.6	481	1.11
Stone and Shen (2002)	2.20%	1.270	7.6	173	1.00
Stone and Shen (2002)	0.55%	0.318	3.8	696	0.98
Stone and Shen (2002)	0.55%	0.635	7.6	173	0.96
Fenzl (1962)	0.81%	0.238	2.4	1808	1.04
Fenzl (1962)	0.20%	0.238	4.7	452	1.01
Fenzl (1962)	0.09%	0.238	7.1	200	1.03
Fenzl (1962)	0.05%	0.238	9.4	113	1.17
Tsujimoto (1990)	0.44%	0.150	2.0	2500	1.19
Cheng and Nguyen (2011)	0.25%	0.650	10.0	76	0.96
Kothyari et al. (2009)	0.25%	0.650	10.0	76	1.07
Present study (Eq. 4.14)	0.25%	0.650	10.0	76	1.05
				Average	1.05
				Standard deviation	0.073

Studies of various investigators reveal that the average values of C_D may be taken as 1.05 for vegetated open channel for both emergent and submerged flow conditions since the value of the standard deviation of C_D computed by various investigators is only 0.073 (Table 5.3). The average computed value of C_D (average of submerged and emergent flow conditions for all the runs) in the present study using Eq. 4.14 coincides with this average value of Table 5.3 and therefore it may be considered for study of other hydraulic resistance parameters and for the study of velocity profiles.

5.6.2. Manning's Coefficient

Manning's roughness coefficient is otherwise called as retardance coefficient or resistance coefficient. It is widely used by the hydraulic engineers for velocity computation in open channel flow. It consists of resistance due to side wall roughness and that due to bed form roughness. Sum of these two terms gives total roughness coefficient. Assuming the uniform flow and that average velocity is uniformly distributed over the entire channel cross section, the roughness coefficient, n is given by Eq. 4.29 as discussed in Chapter 4. In using Eq. 4.29, the value of bed slope, S for all the experimental runs is taken as 0.064% and value of the mean velocity of flow, V_c, is the depth averaged velocity over the entire depth of flow (h) in the channel which is also called the mean channel velocity. Experimental results of Manning's roughness coefficient, n for vegetated open channel flow under submerged and emergent flow conditions at various depths of flows are mentioned in Table 5.4 (a) and Table 5.4 (b), respectively.

Table 5.4 (a) Experimental results of Manning's n, Chezy's C and Darcy-Weisbach friction factor f for submerged flow

Discharge Q (m^3/s)	Flow depth h (m)	Mean constricted channel velocity, V_c (m/s)	Aspect ratio	Manning's n	Chezy's C	Darcy Weisbach friction factor f
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0.0137	0.124	0.190	4.84	0.026	25.38	0.122
0.0173	0.145	0.215	4.13	0.025	27.13	0.107
0.0229	0.17	0.243	3.52	0.024	29.17	0.092
0.0230	0.197	0.271	3.04	0.023	31.03	0.081
0.0389	0.226	0.303	2.65	0.021	33.35	0.070
0.0430	0.245	0.322	2.45	0.021	34.70	0.065

Table 5.4 (b) Experimental results of Manning's n, Chezy's C and Darcy-Weisbach friction factor f for emergent flow

Discharge Q (m^3/s)	Flow depth h (m)	Mean constricted channel velocity, V_c (m/s)	Aspect ratio	Manning's n	Chezy's C	Darcy Weisbach friction factor f
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0.0050	0.060	0.158	10.00	0.022	28.01	0.100
0.0060	0.067	0.156	8.95	0.023	26.43	0.112
0.0066	0.075	0.155	8.00	0.025	25.08	0.125
0.0072	0.083	0.154	7.23	0.027	23.84	0.138
0.0078	0.091	0.153	6.59	0.028	22.89	0.150

The experimental results reveal that values of Manning's n in vegetated open channel flows are more as compared to the value in channel without any vegetation. The values of n in submerged case were found to vary from 0.021 to 0.026 with an average value of 0.023. Similarly the values of n in emergent case were found to vary from 0.022 to 0.028 with an average value of 0.025. Higher values of n in vegetated open channel flow may be due to more resistance offered by the vegetation causing slow and accelerated flow. It is observed that in the submerged flow condition as the depth of flow increases from 0.124 to 0.245 m, values of roughness coefficient decreases from 0.026 to 0.021 (Table 5.4 a). The reason for obtaining lower values of n at correspondingly higher values of depth of flow under submerged case may be due to the fact that larger portion of the area occupied by flow of clear water without any obstruction due to vegetation which behaves like a typical free open channel flow. Consequently, the resistance offered to flow becomes less causing lower values of n. A similar conclusion has been reported by Panigrahi (1987) and Righetii and Armanini (2002).

Values of Manning's n are observed to be more for emergent flow (average value = 0.025) than that for submerged flow case (average value = 0.023). Wu et al. (1999) made extensive studies with artificial roughness to evaluate the retardance value under submerged and emergent case and observed that for a given vegetation density, resistance values are more for emergent case than the submerged case. Unlike submerged case, a reverse trend was noticed in emergent flow condition where values of retardance coefficient are found to increase from 0.022 to 0.028 when the depth of flow is increased from 0.06 to 0.091 m (Table 5.4 b). Similar results have been reported by many investigators. Petryk and Bosmajian (1975) developed a quantitative procedure for predicting Manning's *n* for emergent vegetation. The analytical results showed that the values of n increased as the flow depth increased for a given vegetation density.

However, Shen and Chow (1999) used horsehair to simulate vegetation and their experimental results indicated that under emergent case, the flow resistance decreased as the flow depth increased in turbulent flows. But Kao and Barfield (1978) concluded that drag force by the vegetation blade decides the roughness coefficient in shallow emergent vegetated open channel and the value of roughness coefficient increased as the depth of submergence increased until all the vegetation were completely submerged. After that roughness value decreased as the flow depth increased. Under the condition of low discharge with depth of flow much less than the vegetation height, Fenzl and Davis (1964) found the retardance coefficient gets increased as the depth of flow increased till vegetation undergoes complete bending. After that in the submerged case, values of *n* decreased as the mean channel velocity and hence product of velocity and mean hydraulic radius increased.

5.6.3. Chezy's Coefficient

Chezy's coefficient, *C* was computed by Eq. 4.42 as discussed in Chapter 4 and the computed values are shown in Tables 5.4(a) and Table 5.4 (b) for submerged and emergent flow conditions, respectively. It is observed that as the depth of flow increases, the values of *C* also increases for the submerged case and for the emergent case the trend is reverse. Values of Chezy's *C* range from 25.38 to 34.69 and 22.90 to 28.01 for submerged and emergent flow cases, respectively.

5.6.4. Friction factor

Friction factor *f* is also called as Darcy-Weisbach friction factor, *f,* for all the experimental runs were computed by Eq. 4.39(b) as discussed in Chapter 4. The computed values are presented in Tables 5.4(a) and Table 5.4 (b) for submerged and emergent flow conditions, respectively. Data of both the tables reveal that values of friction factor are high in vegetated open channels ranging from 0.065 to 0.122 for submergence case and 0.100 to 0.150 when the flow is in emergent case. An average value of *f* of 0.090 and 0.125 are obtained for all the runs for submerged and emergent cases respectively. Value of the friction factor, *f,* for vegetated waterway is more than that in a non-vegetated water way. A similar conclusion has been drawn by Panigrahi (1987) who obtained high values of friction factor upto 4.839 for vegetated waterways. The reason of getting higher values of *f* in vegetated open channel may be due to more resistance offered by the vegetation causing slow and accelerated flow. Values of friction factor for submerged case are obtained to be less than the emergent case. The reason of obtaining lower values of *f* at correspondingly higher values of depth of flow under submerged case may be the same as for variations of Manning's *n* with depth of flow as reported earlier. Panigrahi (1987) reported that for cases with depth of flow greater than the height of vegetation, the thickness of the boundary zone approaches a minimum and the portion of the flow passing through the vegetation becomes negligible as compared to that flowing above and hence the friction factor tends to decrease. Under emergent case, as the depth of flow is increased, friction factor was found to increase. This may be because of more resistance offered by the increased frontal area of vegetation with increased depth of flow.

5.6.5. Variation of Resistance Parameters with Aspect Ratio

Variation of Manning's *n*, Chezy's *C* and Darcy-Weisbach friction factor, *f* with aspect ratio (aspect ratio = B/h where B is width of channel = 0.60 m and h is depth of flow) were studied for both submerged and emergent conditions and the relationships are presented in Fig. 5.2 (a, b and c) and Fig. 5.3 (a, b and c), respectively.

5.6.5.1. Variation under Submerged Flow Condition

On the basis of experimental data, it is observed that in the submerged case, as the depth of flow is increased and hence aspect ratio decreased, values of Manning's *n* decreased (Fig. 5.2 a) and the relationship between them is obtained as

$$n = 0.0082 \ln\left(\frac{B}{H}\right) + 0.133 \qquad R^2 = 0.99 \qquad (5.2)$$

Variation of Chezy's *C* with aspect ratios was also studied for various discharges and flow depths and the graphical relationships between them is shown in Fig. 5.2 (b). Chezy's *C* increased with decrease in aspect ratio. The relationship between Chezy's *C* and aspect ratio is given as,

$$C = 52.08\left(\frac{B}{h}\right)^{-0.458} \qquad R^2 = 0.99 \qquad (5.3)$$

Like Manning's *n*, friction factor, *f* was found to vary with different depths of flow and hence aspect ratios. As the depth of flow increased, aspect ratio decreased and correspondingly friction factor also decreased (Fig. 5.2 c). The relationship between them is found to be

$$f = 0.028\left(\frac{B}{h}\right)^{0.916} \qquad R^2 = 0.98 \qquad (5.4)$$

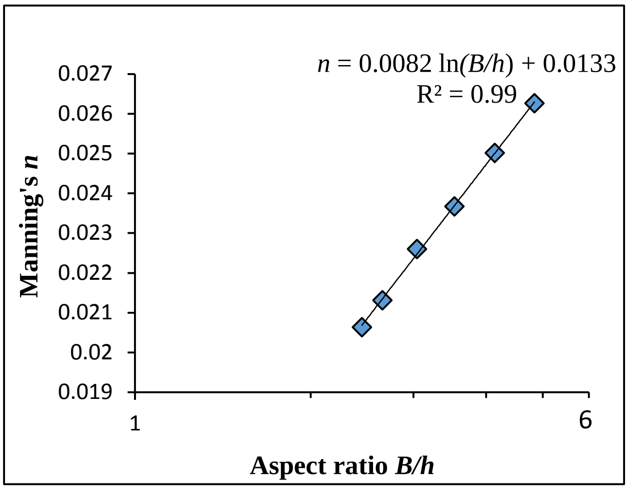

Fig 5.2(a) Variation of Manning's *n*, with aspect ratio *B/h* for submerged flow

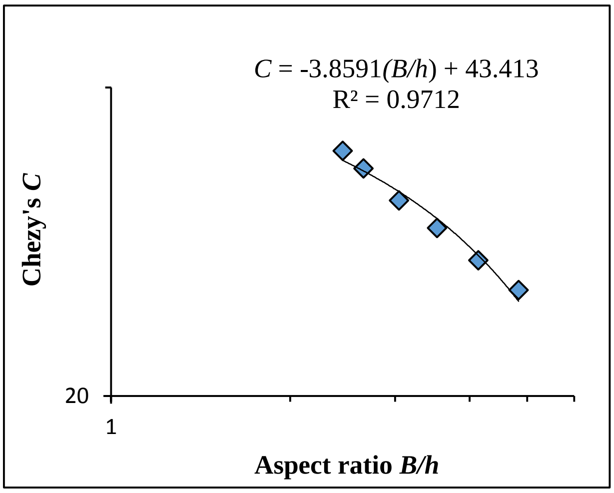

Fig 5.2(b) Variation of Chezy's *C* with aspect ratio *B/h* for submerged flow

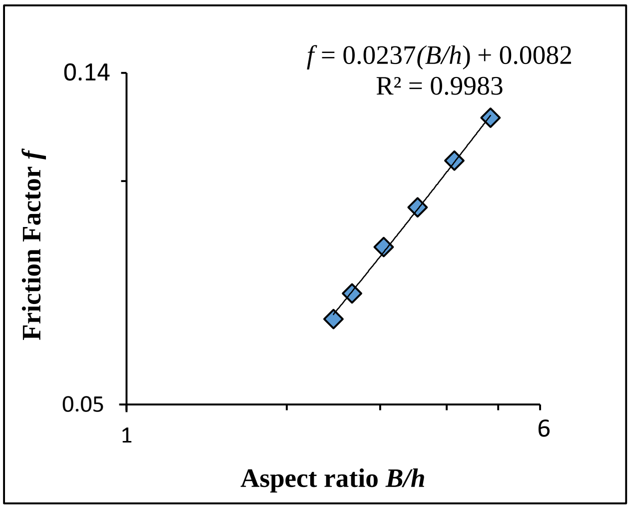

Fig 5.2(c) Variation of Darcy's Weisbach *f* with aspect ratio *B/h* for submerged flow

5.6.5.2. Variation under Emergent Flow Condition

On the basis of experimental data, variations of Manning's roughness coefficient, *n*, Chezy's *C* and Darcy-Weisbach friction factor, *f* with aspect ratios for emergent flow case are presented in Fig. 5.3 (a), Fig. 5.3 (b) and Fig. 5.3 (c), respectively. The relationship between Manning's *n* and aspect ratio is obtained as

$$n = 0.0711(B/h)^{-0.499} \qquad R^2 = 0.96 \qquad (5.5)$$

Similarly the relationship between Chezy's *C* and aspect ratio and that between Darcy-Weisbach friction factor, *f* and aspect ratio are obtained (Eq. 5.6 and Eq. 5.7, respectively) as:

$$C = 9.1735(B/h)^{0.4838} \qquad R^2 = 0.99 \qquad (5.6)$$

$$f = 0.9326(B/h)^{-0.968} \qquad R^2 = 0.97 \qquad (5.7)$$

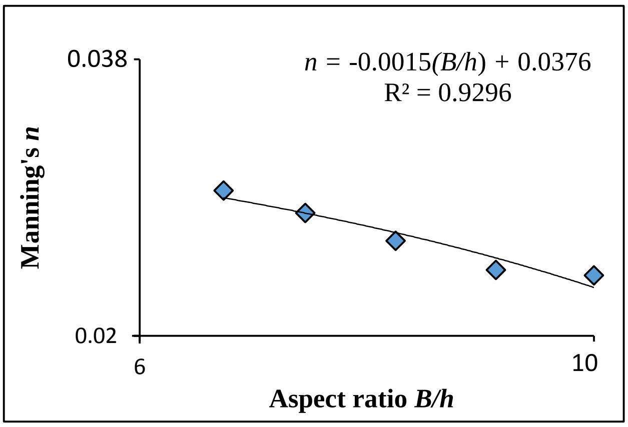

Fig. 5.3(a) Variation of Manning's *n* with aspect ratio *B/h* for emergent flow

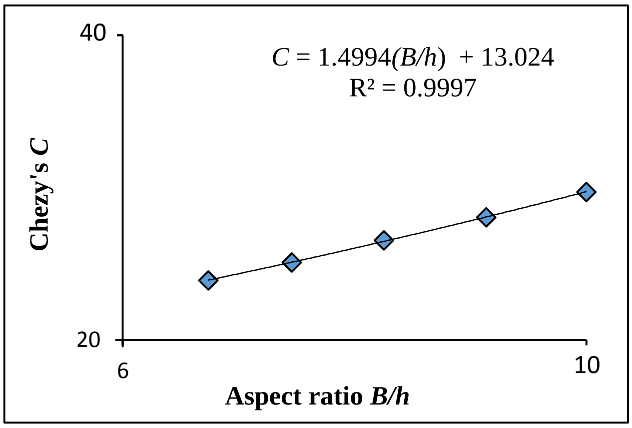

Fig. 5.3(b) Variation of Chezy's *C* with aspect ratio *B/h* for emergent flow

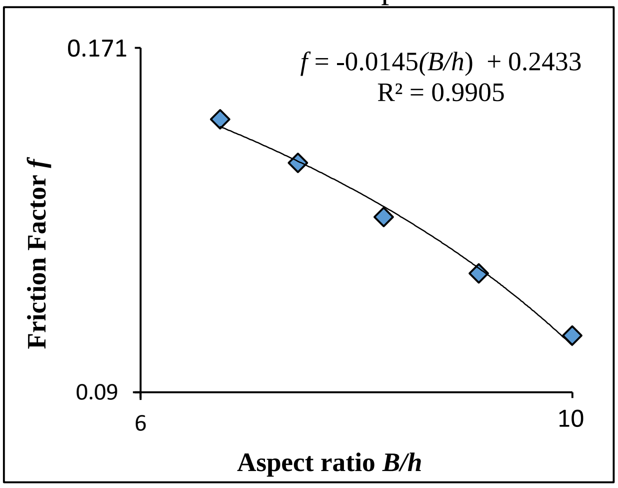

Fig. 5.3 (c) Variation of Friction Factor *f* with aspect ratio *B/h* for emergent flow

Analysis of the experimental data reveals that in the emergent case, as the aspect ratio gets decreased, values of both Manning's *n* and friction factor gets increased but Chezy's *C* got decreased (Table 5.4 b, and Fig. 5.3 a, Fig. 5.3 b and Fig. 5.3 c).

5.7 Variation of Friction Factor with Reynolds Number

Reynolds Number (*Re*) is an important hydraulic parameter frequently used by hydraulics engineer. Values of Reynolds Number were computed by Eq. 4.43 as discussed in Chapter 4 and are presented in Tables 5.5 (a) and 5.5 (b) for submerged and emergent conditions of flow, respectively.

Table 5.5 (a) Experimental results of Reynolds Number for submerged flow

Discharge Q (m^3/s)	Flow depth h (m)	Mean constricted channel velocity, V_c (m/s)	Manning`s n	Darcy Weisbach friction factor, f	Reynolds Number Re x 10^3
(1)	(2)	(3)	(4)	(5)	(6)
0.0137	0.124	0.190	0.026	0.122	16.654
0.0173	0.145	0.215	0.025	0.107	20.934
0.022	0.17	0.243	0.024	0.092	26.329
0.023	0.197	0.271	0.023	0.081	32.127
0.0389	0.226	0.303	0.021	0.070	38.965
0.0430	0.245	0.322	0.021	0.065	43.386

Table 5.5 (b) Experimental results of Reynolds Number for emergent flow

Discharge Q (m^3/s)	Flow depth h (m)	Mean constricted channel velocity, V_c (m/s)	Manning`s n	Darcy Weisbach friction factor, f	Reynolds Number Re x10^3
(1)	(2)	(3)	(4)	(5)	(6)
0.0050	0.060	0.158	0.022	0.100	7.906
0.0060	0.067	0.156	0.023	0.112	8.553
0.0066	0.075	0.155	0.025	0.125	9.305
0.0072	0.083	0.154	0.027	0.138	9.979
0.0078	0.091	0.153	0.028	0.150	10.665

It is observed that Reynolds Number increases with the increase in flow depth, *h,* under both submerged and emergent flow case. Relationship between Reynolds Number and friction factor is shown in Fig. 5.4 (a) for submerged case and that for emergent case is shown in Fig. 5.4 (b). It is observed that as Reynolds Number increases, friction factor decreases for flow in submerged case as is clear from Fig. (5.4 a). However, for emergent case, the trend is reverse as is shown in Fig. (5.4 b). The relationship is presented as Eq. 5.8 for submerged case and Eq. 5.9 for emergent case.

$$f = -0.05\ln(\mathrm{Re}) + 0.677 \qquad R^2 = 0.99 \qquad (5.8)$$

$$f = 2 \times 10^{-5}(\mathrm{Re}) - 0.043 \qquad R^2 = 0.97 \qquad (5.9)$$

Kouwen and Unny (1973) observed that, at the erect emergent condition of vegetation, friction factor varies proportionately with the Reynolds Number. However, at high discharges with high depths of flow, vegetation undergoes bending and at that time, friction gets reduced when the Reynolds Number is increased. Murota et al. (1984) also reported that within the range of Reynolds Number from 10000 to 25000, friction factor of vegetated open channel decreased as the Reynolds Number increased. In submerged flows, the flow area increases in comparison to the frictional area thereby increasing the inertia force leading to the agreement of the conclusion that the frictional force increases with decrease in Reynolds Number confirming with the experimental results.

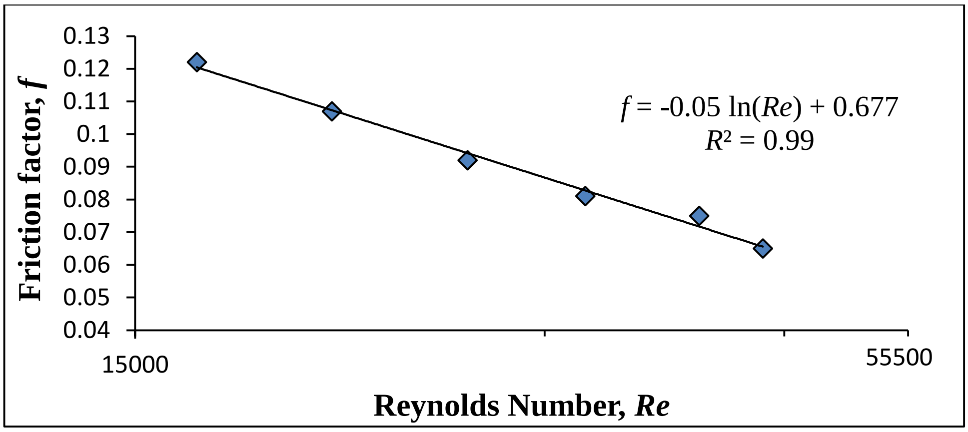

Fig. 5.4 (a) Relationship between friction factor and Reynolds Number (submerged flow)

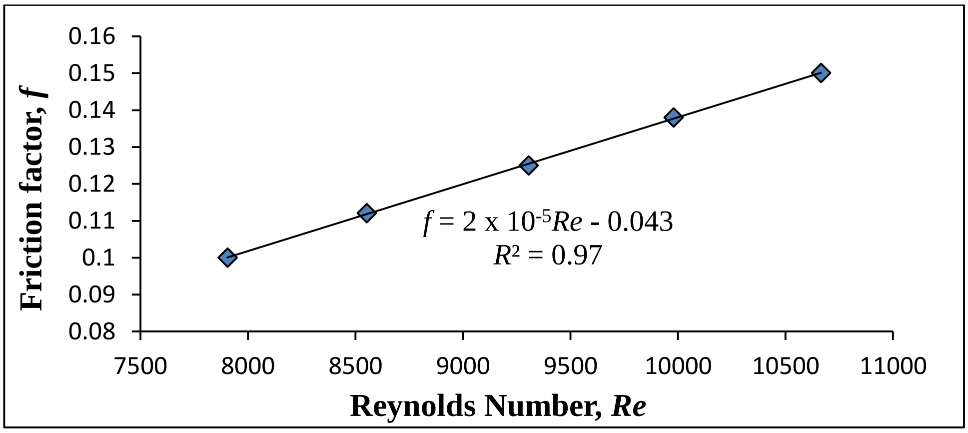

Fig. 5.4 (b) Relationship between friction factor and Reynolds Number (emergent flow)

5.8. Velocity Profile

As discussed in Chapter 3, velocity at various longitudinal distances along the path perpendicular to flow direction were measured by ADV as well as Pitot tube for each experimental runs in the vegetated open channel under both emergent and submerged cases. Velocities were measured at every 0.1 *h* intervals where *h* is the flow depth. These measured values of velocities were used to plot velocity profiles and the values were used for study of velocity distributions.

5.8.1. Emergent Flow

An open channel flow can be divided vertically into two major layers: (i) a near-bed layer and (ii) an outer layer above. Both the layers overlap in part. The lower layer is observed to be the roughness layer or stem/vegetation layer which is influenced predominantly by roughness elements. Emergent condition is the limiting condition of submerged condition without surface layer. Generally the flow velocity is always smaller in the stem layer in comparison to the surface layer since the former undergoes the drag effect.

In the present study, velocity profiles of vegetated open channels were drawn for 5 different depths of flow under emergent case and are shown in Figs. 5.5 (a) to (e) for different depths ranging from 6.0 to 9.1 cm. It is observed that velocity profile is normally uniform along the depths of emergent cases. Laboratory studies of Tsujimoto and Kitamura (1990) also reveal the same thing that velocity profile is normally uniform along the depths for flow in emergent cases. Bed friction shows its effect on the velocity profile shape only near the bed where it reduces to zero. Brunet et al. (1994) reported that presence of submerged vegetation serves as large-scale roughness to obstruct the near-bed flow and thus reduce the flow velocity. If the surface flow becomes very shallow, the roughness sub-layer may extend up to the free surface and thus the logarithmic layer would become thinner and might even be absent.

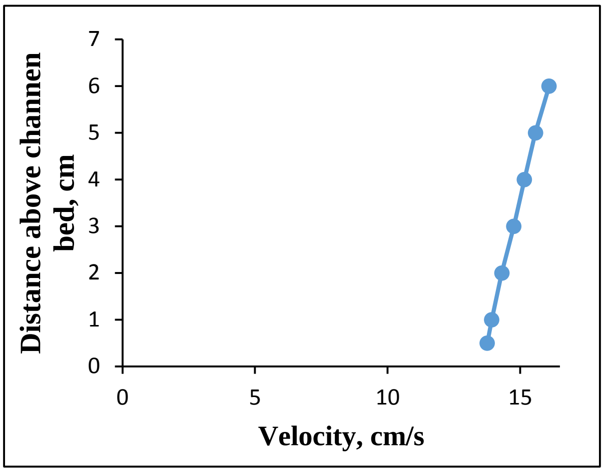

Fig. 5.5 (a) Vertical velocity profile, *h*=6.0 cm

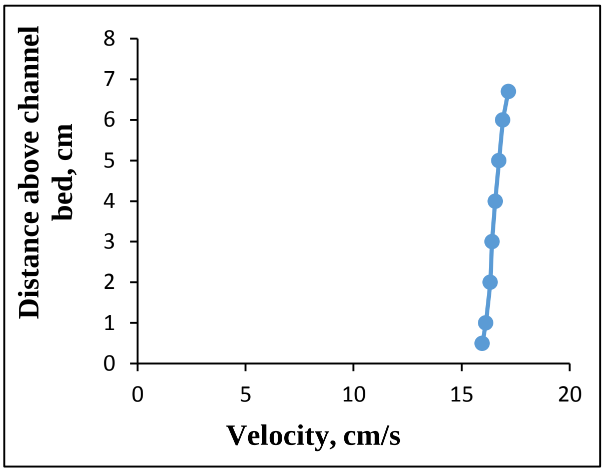

Fig. 5.5 (b) Vertical velocity profile, *h*=6.7cm

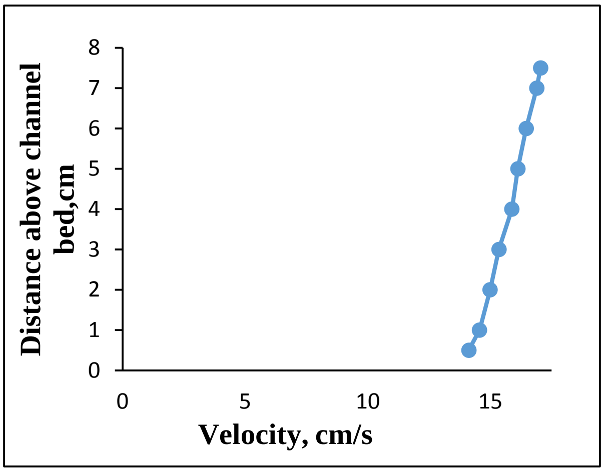

Fig. 5.5 (c) Vertical velocity profile, *h*=7.5 cm

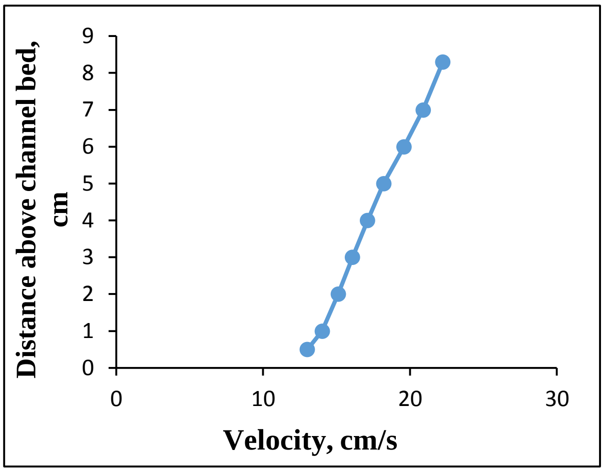

Fig. 5.5 (d) Vertical velocity profile, *h*=8.3 cm

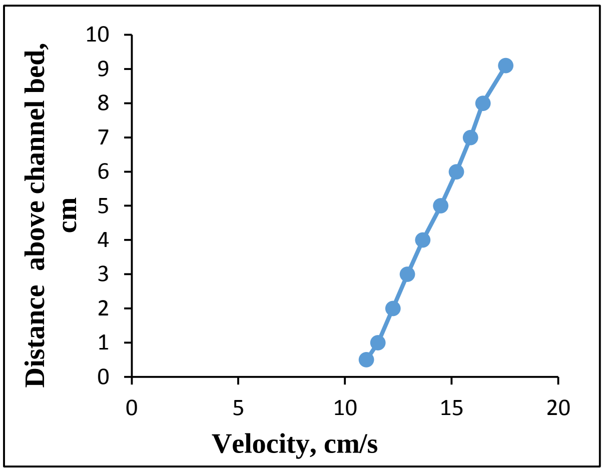

Fig. 5.5 (e) Vertical velocity profile, *h*=9.1 cm

5.8.2. Submerged Flow

In open channel flow with submerged vegetation, the outer layer is the surface layer which is above stems which contains practically no roughness. In the surface layer, there exist significantly greater velocities in comparison to stem layer. For submerged flow depths, however the stem layer velocity will approach a constant value in reference to the shearing effect in the surface layer. The flow through the near-bed vegetation layer differs from that in the surface layer above. Fig 5.6 (a) to (f) presents vertical velocity profiles at various depths of flow from 12.4 to 24.5 cm of the experimental channel under submerged case, respectively. From these figures, it is observed that the velocity profile in all runs is found to be two layered. Velocity within the vegetation layer is found to remain almost constant and does not change with depths from the channel bed. But after submergence, velocity increases with increase in depth from the channel bed and the velocity profile is found to follow logarithmic law. Similar conclusions have been drawn by Temple (1986), Sumer et al. (1996), Cheng and Chiew (1998) and Cheng et al. (2008).

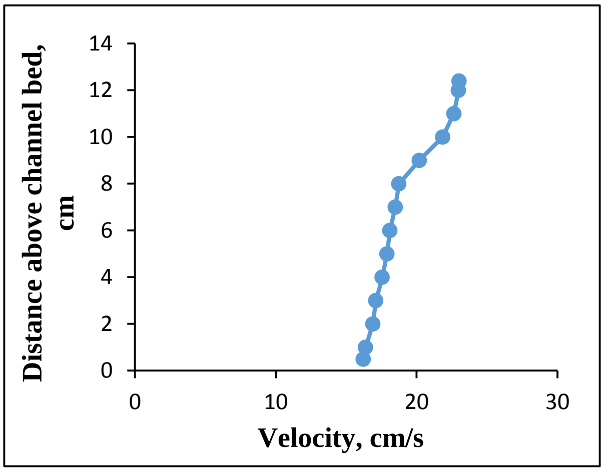

Fig. 5.6(a) Vertical velocity profile, h=12.4 cm

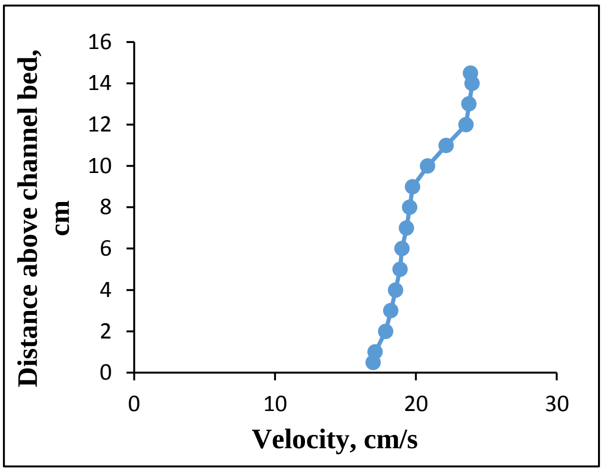

Fig. 5.6(b) Vertical velocity profile, h=14.5 cm

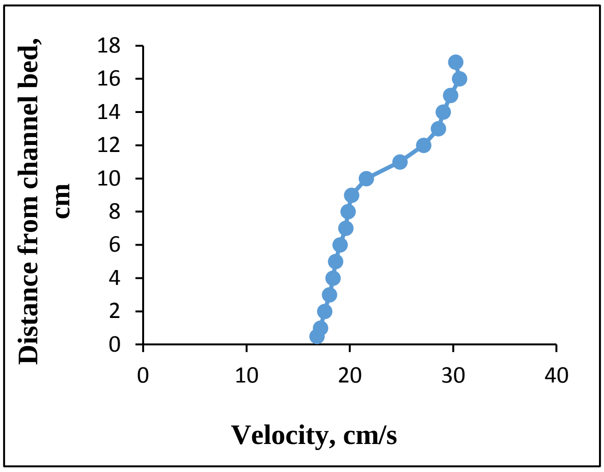

Fig. 5.6(c) Vertical velocity profile, *h*=17 cm

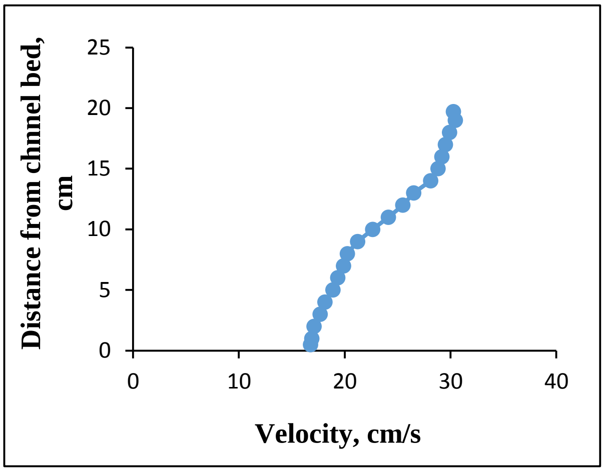

Fig. 5.6(d) Vertical velocity profile, *h*=19.7 cm

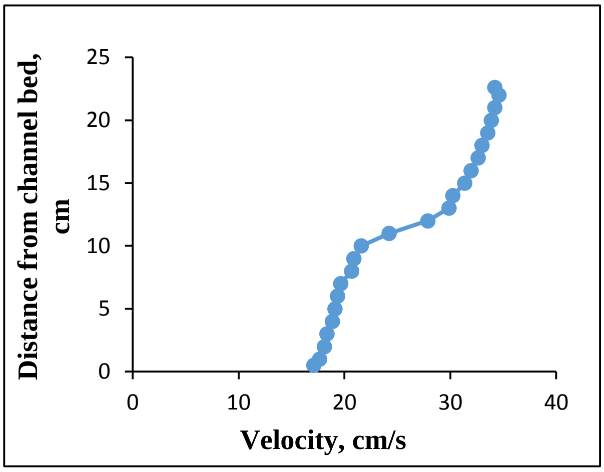

Fig. 5.6(e) Vertical velocity profile, *h*=22.6 cm

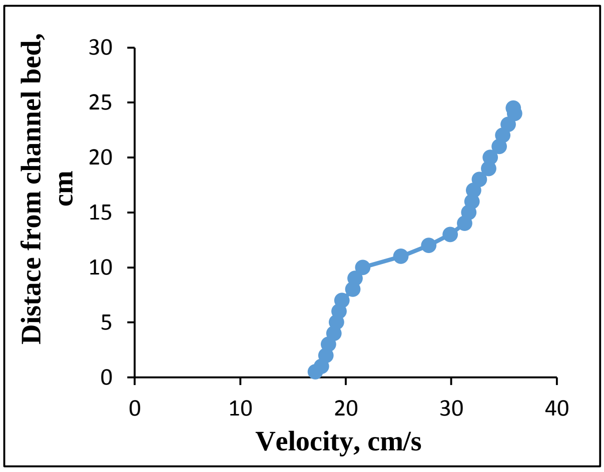

Fig. 5.6(f) Vertical velocity profile, *h*=24.5 cm

5.8.3. Velocity through Stem/Vegetation Layer

Velocity through vegetation called stem or vegetation layer's depth averaged velocity *(V_l)* under both submerged and emergent flow cases were calculated by Eq.4.45 (Stone and Shen, 2002). In the emergent case, l^*= 1 for all the experimental runs whereas for submerged case, values of l^* are less than 1 and change with depth of flow. Using the experimental data and assuming an average value of C_D of 1.05 (as mentioned in Table 5.3), stem layer's depth averaged velocity under both submerged and emergent cases were calculated. These velocities were compared with the depth averaged velocity based on measured ones in Fig. 5.7 (a) for submerged case and in Fig. 5.7 (b) for emergent case. In the same figure, values of stem layer velocities reported by other investigators are also plotted and the velocities are compared. The close agreement between measured and calculated stem layer velocities (V_l) shows that the velocity in the stem layer can be accurately estimated for both emergent and submerged case by Eq. 4.45, using the approach of Stone and Shen (2002).

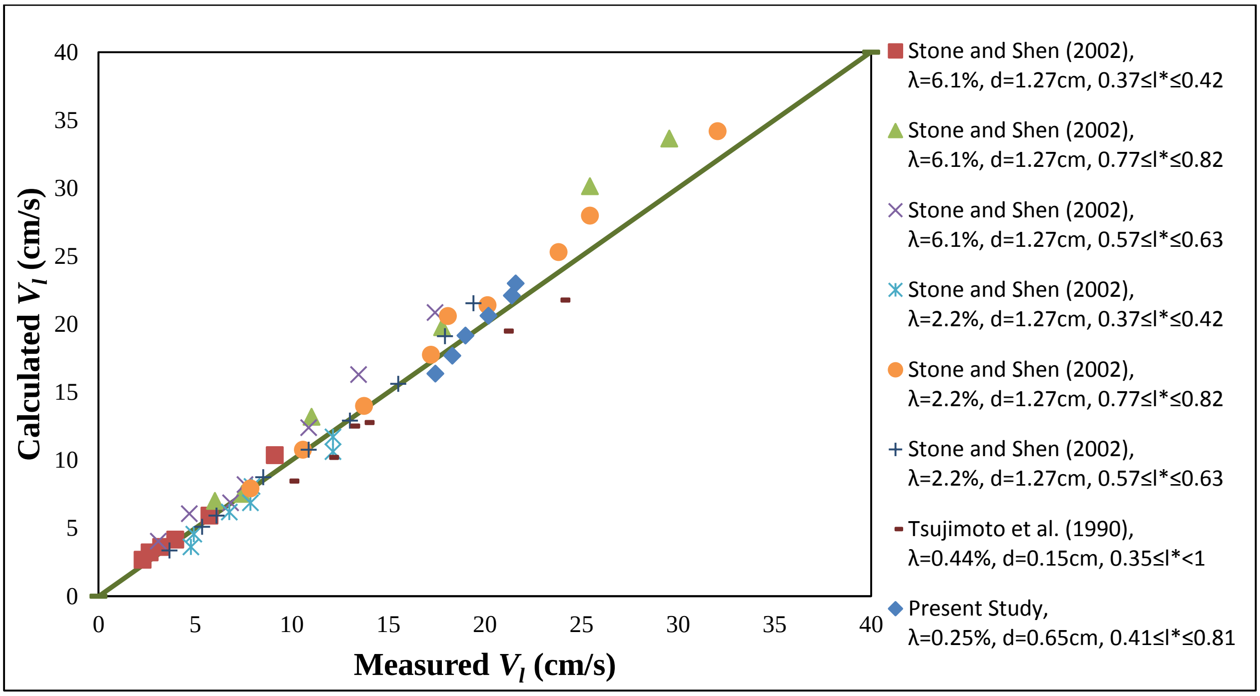

Fig. 5.7 (a) Measured vs calculated stem layer depth averaged velocity for submerged flow

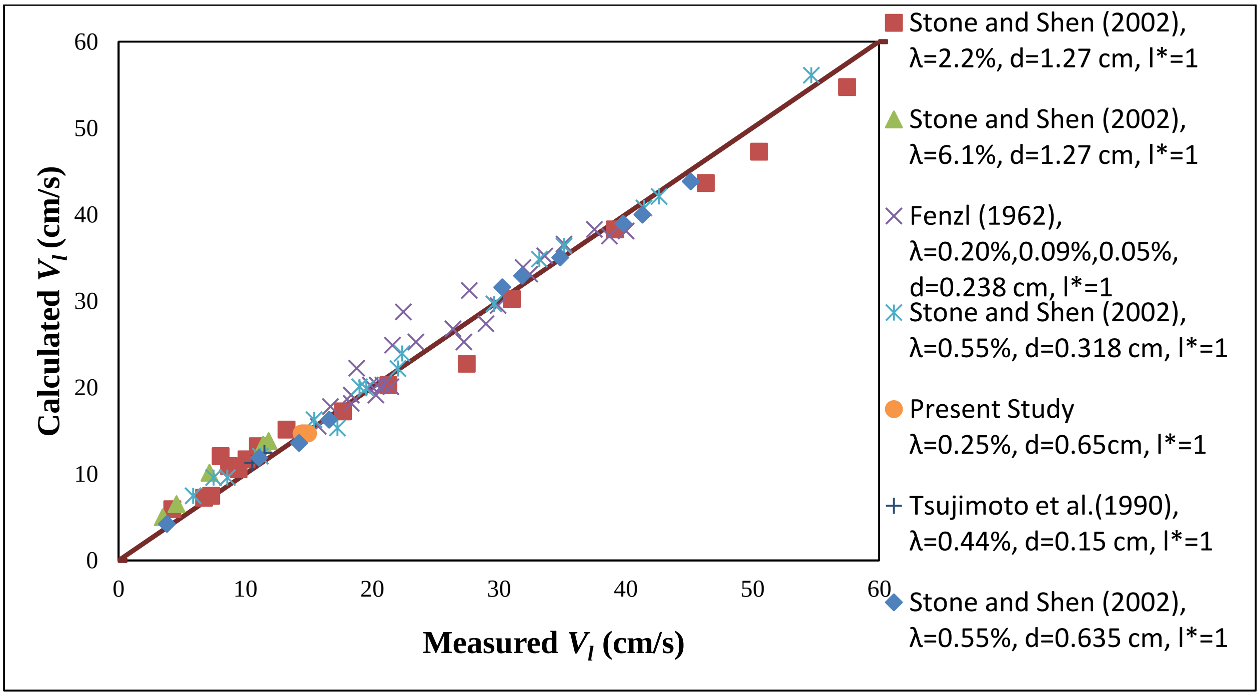

Fig. 5.7 (b) Measured vs calculated stem layer depth averaged velocity for emergent flow

5.8.4. Mean Channel Velocity

The mean channel velocity which is the cross sectional averaged velocity, V, is estimated by Eq. 4.47 (Stone and Shen, 2002) for submerged case. Value of C_D in this equation is taken as 1.05 (average C_D value as reported in Table (5.3).Values of N = 76, λ = 0.0025, S = 0.00064 and d = 0.0065 m are considered for all experimental runs in the study. The estimated velocities were compared with the measured velocities in Fig. 5.8 for submerged case. For the emergent cases, estimated velocities by Eq. 4.48 were same for all flow depths and so could not be compared with the measured velocities. In fact the measured velocities in all depths in emergent cases were found to be almost same. The close agreement between measured and estimated velocities in submerged case shows that mean channel velocity can be accurately estimated by Eq. 4.47. This constant value of C_D of 1.05 used in Eq. 4.47 estimates the mean velocity by Equation of Stone and Shen (2002). The average value of C_D of 1.05 is less than the C_D measured in present experimental runs. When the C_D value decreases the estimated mean velocity increases as is found in Eq. 4.47 since other factors remain constant.

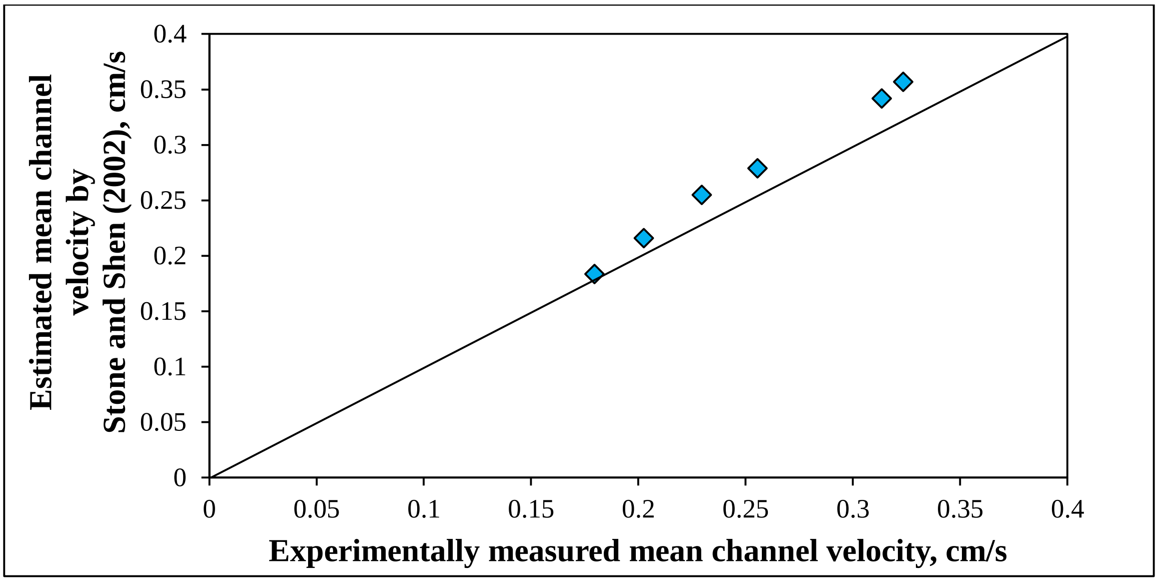

Fig. 5.8 Mean channel velocity vs measured velocity for submerged flow

CHAPTER 6

CONCLUSIONS

Experiments were undertaken in vegetated open channel in a tilting hydraulic flume at the Fluid Mechanics Laboratory of National Institute of Technology, Rourkela, Odisha (India) under both emergent and submerged flow conditions at various discharges and flow depths. Cylindrical rigid iron rods of height 10 cm and diameter 6.5 mm plated in staggered pattern in the flume with a vegetal density of 76 per bed area of 1 m^2 are used to simulate vegetation in open channel. Following salient findings are obtained from the present research work.

- Unlike open channel flow without any vegetation, the various hydraulic resistances like vegetal drag coefficient, C_D, Manning's roughness coefficient, n, and Darcy-Weisbach friction factor, f are found to be dependent on depth of flow in channel, ratio of wetted stem length to depth of flow in channel called submergence ratio, l^*, vegetation planting patterns and vegetation/stem density, λ.
- Drag coefficient C_D decrease with increasing depth of flow indicating that at higher depth of flow or at lower submergence ratio, flow inside the surface layer is predominant as compared to the vegetation layer, which offers some resistance to flow.
- Drag coefficient C_D for emergent case are observed to increase with increasing flow depths which indicate that the resistance offered to flow is more in the vegetation layer with less velocities being concentrated in the vegetation layer.
- Manning's roughness coefficient, n, and Darcy-Weisbach friction factor, f, in vegetated open channel flow are found to depend on depth of flow and submergence ratio. At higher depths of flow and hence less submergence ratios, velocity of flow in the surface layer is found to increase and resistance to flow decrease. This results in obtaining decreasing values of retardance coefficient in the surface layer of vegetated open channels.

• Under emergent flow case, values of Manning's roughness coefficient are observed. Unlike submerged case, flow is entirely in vegetation layer in emergent flow case and the drag coefficient plays vital role in deciding the flow resistance. As the discharge and flow depth increase in the emergent flow case, more resistance is offered by the increased frontal area of vegetation. Consequently the retardance factor increases.

• Measurement of flow velocity at different points in vertical section of flow depth indicate that under the emergent flow case, velocity of flow within the stem layer is one layered with almost a uniform and constant velocity at various vertical distances. However under submerged case, when the depth of flow increases, velocity profile is two layered.

Suggestions for Future Research

The present research leaves a wide scope for the future investigators to explore many other aspects of vegetated open channels. The flow resistances have been determined with limited data of flow discharges and depths. Wide range of flow discharges and depths could not be achieved due to limited pump capacity. It is expected that future investigators would carry on the research to find out the different hydraulic parameters at wide range of discharges and flow depths, channel bed slopes and various vegetation characteristics like height, thickness, planting patterns and density of vegetation. Effect of boundary and side wall shear stress on flow hydraulics in vegetated open channels need to be studied in the future research. Moreover, the effect of wake formation behind the roughness element in an array of identical roughness elements on flow resistance and velocity profile also needs an elaborate study. The vegetative rough floodplain can be studied for compound channel with main channel of different roughness'. The work could also be extended for meandering, skewed and non-prismatic channel with vegetation.

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